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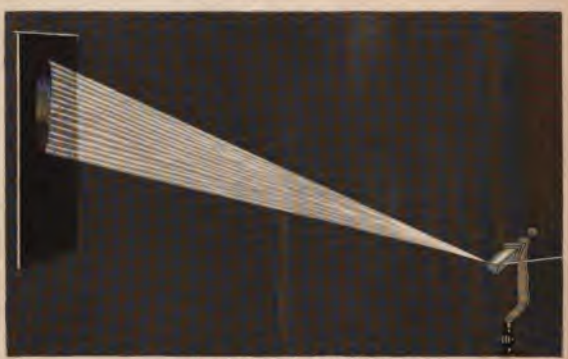
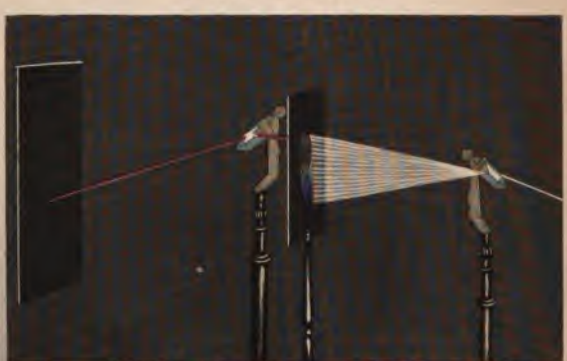
Spectrum showing the absorptive power of Sodium vapour (Fig.6)



Solar Spectrum (Fig. 5)



Actions of a prism on a ray of light (Fig. 7)

THE

PHENOMENA AND LAWS

OF

HEAT.

BY ACHILLE CAZIN,

PROFESSOR OF PHYSICS IN THE LYCEUM OF VERSAILLES.

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be no manner of doubt. It is no part of their business, and they do not pretend to deduce from the correlation they observe between heat and the sensible or atomic movements of bodies, any conclusion relative to the constitution of the universe. Nothing could be more unfair than to allege that their opinions lead to the negation of a primal force, and thus to materialism. A distinguished writer on Physics, M. Hirn, has even demonstrated, in his *Exposition de la Théorie mécanique de la Chaleur*, that the experimental principles upon which they depend result logically, neither in materialism nor pantheism, but in the purest spiritualism. The essential character of the new theory of heat is to show the connexion of phenomena, in a continued chain, viewed independently of their causes; that is to say, without taking into consideration the nature of the forces which produce them."

The reader of this little Treatise, therefore, will not expect to find anything in its pages but a simple account of phenomena; and he is requested to bear in mind that the first cause of heat is never brought into question. With regard to the translation, it is only fair to observe that it is never easy to render a technical work from one language into another. To secure accuracy, the writer has availed himself of the professional knowledge of his son, whose scientific aptitude encourages the hope that he may hereafter take the responsibility of more important

FELL HILL,
1868.

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WEIGHTS AND MEASURES.

In general, throughout the following treatise, the figures of the Frenc metric system have been placed in juxtaposition with their Engli equivalents, or the latter have been substituted for them. In son instances, this could not be done without an entire reconstruction the author's argument. The following short table of equivalent weigh and measures may therefore be found useful :—

1 kilogramme	= 2·205 lbs. avoirdupois.
100 do.	= 1 cwt. 3 qrs. 24·462 lbs.
1 gramme	= 0·544 drams avoirdupois.
100 do.	= 3 oz. 8·438 drams avoirdupois.
1 metre	= 39·37079 inches.
1 decimetre	= 3·937079 ,,
1 centimetre	= 0·3937079 ,,
1 millimetre	= 0·03937079 ,,
1 kilometre	= 1000 metres = 1093·63305 yards.
1 cubic metre	= 61027·051 + cubic inches.
1 ,, decimetre	= 61·02705 + ,, ,,
1 ,, centimetre	= 0·06112 + ,, ,,
1 litre	= 1 cubic decimetre = 1·760 + pints.
1 decilitre	= 0·1760 + pints.
1 centilitre	= 0·0704 + pints.

THE THERMOMETER.

The range of temperature from the freezing to the boiling point c water is divided by Fahrenheit's scale into 180 portions or degree numbered from 32° to 212°.

In the Centigrade scale the same range of temperature is divided int 100 parts, numbered from 0 to 100°.

Hence, to convert degrees of Fahrenheit into Centigrade, subtrac 32, and multiply the remainder by $\frac{5}{9}$, and—

To convert Centigrade into Fahrenheit, multiply the Centigrade b $\frac{9}{5}$, and add 32 to the product.

THE

PHENOMENA AND LAWS OF HEAT.

CHAPTER I.

GENERAL PHENOMENA OF HEAT.

1. *Our ordinary perceptions of Heat distinguished from its proper phenomena.*

WHEN we touch any of the bodies that surround us, we generally recognise a difference in their state; some communicate to us the sensation of heat, others that of cold. This difference is merely relative to our sensations; it depends on the fact that the sense of touch undergoes a particular modification, which causes a sensation to be experienced, and a judgment to be formed concerning it, practically at the same moment. This special sensibility is given to us that we may always be on the watch for our preservation. But it is not this kind of action with which we are concerned in the present work. We have to investigate heat and cold apart from ourselves as exhibited by inanimate bodies. We have to discover what phenomena occur when such bodies act one upon another; what modifications they undergo in becoming hot or cold. And in the degree that these modifications impress our senses we shall make those impressions also contribute towards the judgments we have to form. In most cases the sense of sight will reveal what is taking place; but it may happen that our hearing *or our sense of smell* may also be called upon to

assist in the observation. It is thus that the human mind collects the various data furnished by the senses, and makes such an orderly arrangement of observed facts as to obtain a knowledge of nature.

The following striking example will teach us to be ever on our guard against the sense of touch when heat is in question. Plunge the right hand into a vessel of tepid water and the left into one of iced water. Then put them both into water of the ordinary temperature. The latter will now appear to be cold, if we decide according to the sensation experienced by the right hand, but warm if we judge by our left; and yet in both cases it is the same water, having the same uniform temperature. The different manner in which we prepared our hands is the sole reason why we experience different sensations.

The same thing takes place when we pass immediately from a hot bath into the open air—the temperature feels cold. But if we pass out of a cool room or vault into the same atmosphere as before, it will seem to be warm.

It thus appears that there is no essential difference between heat and cold when we abstract our sensations, and consider only the body which impresses us. The action of heating is simply the inverse of that of cooling, and the word *heat* designates the *cause* of this kind of action.

Let us now prepare ourselves to study this subject by separating from amongst the thousand phenomena presented by nature those which belong to heat. It is certain that our first view will be very incomplete; but as we advance we shall become better observers, and at every step a new discovery will recompense our toil, and urge us to further advances. We may not succeed in seeing and understanding all that we desire; but we may, at least, derive profit from the study in proportion to our means, and the intelligence we bring to bear upon them.

2. *Heat produced by the atomic movement which produces chemical action.*

We are in the midst of winter; the surface of the earth is white with snow, the rivers are frozen over; but the room

we inhabit is warmed by a brilliant fire. These conditions are admirably well adapted for the commencement of our investigations.

What is a fire? What, for example, takes place in the grate? We must here have recourse for a moment to the science of chemistry; but at present our object is only to obtain from it some two or three very simple ideas, requiring a very slight effort of the intellect to comprehend.

The combustible substance burns in a current of air, which enters the room through the interstices of the doors and windows, and rises in the chimney after passing over the coals. This air becomes modified in the act of supporting combustion. Air is formed of two parts—the one called nitrogen, the other oxygen. It is the latter which gives rise to the phenomena of combustion whilst uniting itself to the carbon; and by this union carbonic acid gas is produced, which escapes up the chimney in company with the nitrogen. We need not enter into a detailed explanation of this phenomenon, our object being to concentrate our attention on the subject of heat.

The action which takes place in this chemical combination may be somewhat understood by imagining oxygen and carbon to be formed of particles called atoms, which rush together and unite in one body when they are brought sufficiently near each other. It is this sudden rush or shock of the particles which causes combustion. It produces at once heat and light; for the flame that we see is only a phenomenon which takes place over the coals, and which we judge of according to the impression it makes on our eyes.

Are we then to understand that there can be no chemical combination producing heat without the simultaneous production of light? Take a single example from a thousand that might be cited to prove the contrary. Powdered sulphur is mixed with iron filings, and a hole being made in the ground, it is filled with the mixture, which is afterwards covered with earth and watered; in a little time the mass heats spontaneously. swells up, raises the earth, and disengages vapours. This experiment was first made by Nicolas Lémery, a chemist of the seventeenth century, who was

is accompanied with the disengagement of heat and light; thus heat causes the sulphur, which the phosphorus covered, to burn, so that it also combines with the oxygen of the air to form sulphurous acid gas. Finally, this combustion, first of the phosphorus and afterwards of the sulphur, determines that of the wood of which the match is composed.

It will be sufficient for our purpose to analyse what happens in the case of the phosphorus, as the same reasoning applies to the sulphur and the wood. The atoms of phosphorus are united by a force called cohesion, which force opposes itself to their combination with the atoms of oxygen. The rays of heat which come from the fire put these atoms in motion, acting like some actual force capable of destroying cohesion, and rending the atoms apart. When this happens, the atoms rush to unite themselves with the atoms of oxygen, and phosphoric acid results.

We have thus briefly studied a case of combustion determined by heat in concurrence with the air. There are other cases of combustion in which air plays no part, and which may be effected when the combustible is placed under the exhausted receiver of an air-pump.

Soak a bit of cotton in a mixture of equal weights of sulphuric acid and fuming nitric acid; afterwards wash it with abundance of water, and you will obtain gun-cotton; that is to say, cotton combined with a certain quantity of oxygen and nitrogen. If brought near a fire, it will instantly ignite and disappear, without leaving any visible traces. Evidently the atoms of which the gun-cotton was composed have been separated from one another by the action of heat, and they have recombined in another form as gases, which the air has forthwith carried away. If a more complete chemical explanation is desired, the case may be stated as follows:—Gun-cotton is a combination of carbon, hydrogen, oxygen, and nitrogen. When the heat of the fire has disassociated these four kinds of atoms, they recombine in the following order: the carbon and a part of the oxygen form carbonic acid gas, the hydrogen and the rest of the oxygen form vapour of water, and the nitrogen remains free. This is all done so quickly, that gun-cotton can be

burnt in the hand without causing the sensation of heat; a great flame is produced, which instantly disappears, leaving no trace if the gun-cotton has been properly prepared.

The action which takes place in the combination of gunpowder is essentially the same. Gunpowder is a mixture of saltpetre, charcoal, and sulphur. Decomposed by heat, its atoms enter into a fresh arrangement, producing carbonic acid gas and nitrogen gas, and leaving a brown compound of sulphur and potassium. It is the great bulk of gas which, developed in a fire-arm, presses against its sides, and drives out the cannon-ball.

As the facts we have enumerated belong to chemistry, we need not dwell upon them any longer. They are sufficient to give us a notion of the constitution of bodies, which may be defined as assemblages of particles bound together by cohesion, and which heat tends to separate, acting like a force contrary to cohesion. In the phenomena specially treated by physics, the particles are not supposed to change their nature; they simply separate from or come nearer to each other, or change their respective positions, always in themselves remaining identically the same. They are called molecules, and they must not be confounded with atoms, which may be of different kinds in the same body, and which go to form molecules. Thus water is an assemblage of like molecules; each molecule is composed of two atoms of hydrogen and one atom of oxygen. Here we only study those phenomena in which there is no separation between the atoms, and in which the molecules alone act a part.

6. *Change of bulk effected by Heat.*

Take a copper cylinder or ball, and a ring through which it can pass freely. Then let the cylinder or ball be heated for some time in a fire, and it will be found that it can no longer pass through the ring. After being cooled, however, it will again pass freely as before; from which the inference is plain—that copper expands by heat and contracts by cold. Hence one of the physical effects of heat is to change the volume of substances. We can form an idea of the *rationale of this* change by imagining the mole-

cules to recede from, or to approach to, one another. It follows, also, that they do not really touch each other, a certain force keeping them always at a proper distance, in the same way that gravitation keeps the earth and othes planets at determinate distances from the sun, and uniter the innumerable globes which fill the universe; for each star is a sun, which has its attendant planets, and is the centre of a movement which follows the plan traced by the Creator. Do not forget this general resemblance between the world of molecules and the worlds which revolve in the starry heavens. A universal law rules over the movements and the positions of both. We have not yet discovered this law; but it is a great deal to have already suspected its existence, to have included in the same sentiment of admiration these two harmonies, differing only in their proportions: the one presiding over masses infinitely small, which we touch; the other over masses which we may call by comparison infinitely great, and which are revealed to us by instruments which enable us to explore the immeasurable profundities of space.

7. *Fusion and solidification.*

Here is a piece of ice, which we place in a glass vessel near the fire. It melts, and in the place of the solid ice we have soon an equal weight of liquid water. If now we expose this same water to the sharp cold which reigns out of doors, it will freeze again. This transformation is the effect of heat. To melt ice it must be submitted to the action of bodies warmer than itself; to freeze water it must be submitted to the action of colder bodies. The two operations are of the same kind, but both are inverse the one to the other. The sun will gradually bring about the same phenomena in a field covered with snow. By its heating action the white needles which cover the trees, and whose marvellous ramifications are so much admired by all observers of nature, will be reduced into drops of water, which will fall to the earth; the carpet of snow which preserves the soil from the too sudden variations in the temperature of the air will diminish in thickness; and the

water that results will impregnate the earth, and, reanimating the germs contained in it, will restore to it its fertility.

At nightfall, under the clear starlight, the fusing process ceases. The force which produced the result has disappeared; but more than this—the celestial space is much colder than ice. Thus a part of the water melted during the day will freeze again; and several sunny days must succeed each other before the snow will completely disappear. Life will thus be revived little by little, and the danger that would attend a too sudden change will be avoided.

8. *Evaporation, ebullition, and condensation of vapours.*

Fusion, as we have seen, is one of the effects of the action of heat upon solid bodies. There is another effect which is manifested on some solids, but more especially on liquids. During a very sharp cold, a little snow left in the open air on a plate may disappear completely without having suffered fusion. The same thing happens to camphor if put in a large glass bottle. Little crystals are deposited here and there on the interior, changing place slowly if the position of the bottle be changed. Let us inquire what has happened in this case.

We shall find on investigation that vapours have been formed on the surface of the camphor; their molecules have receded from one another, and constitute a true gas, which seeks to diffuse itself throughout all parts of the bottle. Some of these parts being colder than others, the vapours condense at those particular places, and again take the solid state by an action inverse to that of vaporization. Thus heat has transformed the camphor into vapour, and cold has made it once more assume the solid state. It is to this property that we owe the odour of camphor. Its vapours enter our nostrils and act on the organ of smell; the same thing happens in the case of all odorous solids.

Liquid substances, however, evaporate most easily. After rain the stones and pavements dry very quickly in the sun, a phenomenon which evidently cannot be referred to absorption. Take a sheet of paper, weigh it, and then moisten

it with water; the moisture quickly disappears. Weigh it again, and it will be found to possess exactly the same weight as before. What has become of the water? It exists in a state of vapour, mixed with the air by which we are surrounded, and is therefore not visible. To see the vapour thus disengaged resume the liquid condition, get a decanter of cold water fresh from the well or cellar, and well corked, so that none may come out. Much time will not elapse before dew will be seen deposited on the surface of the glass. This happens because the bottle of water has cooled the air of your chamber, and the vapour of water naturally contained in it has been condensed. The atmosphere which surrounds the terrestrial globe, and which forms a gaseous ocean forty miles in depth, evidently contains vapour of water, arising from the evaporation of seas, rivers, and streams. When the sky is very clear, this water remains as an invisible transparent gas; but various causes here and there determine its condensation, and from this arise clouds, fogs, rain, hail, and snow, circumstances determining which. We shall have to observe all these phenomena, and we shall try to discover the harmony of the laws by which they are all regulated.

Let us return to our observations near the fire. We have water boiling in an open vessel; its vapour rises like a little cloud, and we can see bubbles detach themselves from the inside, rise, and break on the surface of the liquid. This again is the reduction of a liquid to the state of vapour; but, instead of being superficial, it is effected at various points of the mass. This phenomenon is called ebullition: the action of heat is the same in this case as when it causes evaporation. It is simply quicker in its action, and is spread over a great number of points.

Thus water has become known to us in the three different states of ice, of a liquid, and of vapour or gas. Its molecules are always identical in themselves, but they are unequally bound together in these three states. In the solid there is a strong attraction between the molecules; in the liquid they can roll easily over one another; and in the gaseous condition they recede from one another, pressing

against obstacles. These different conditions may be predicated of a great number of substances.

9. *Mechanical effects of Heat.*

The following little experiment will enable us to form an idea of the expansive force of vapour. Fig. 1 represents

FIG. 1.—Recoiling Æolypile.

a copper ball carried on wheels. The ball is hollow; some water has been poured into it through a tubular opening, which has been closed hermetically with a cork. The tubular opening thus tightly corked has been turned into a horizontal position. A small spirit lamp has been placed on the carriage under the ball, and being lighted, its flame heats the water; the cork is thrown out to a distance with the noise of an explosion, a jet of vapour issues from the pipe, and the carriage is driven back. Now to explain what has happened.

The heat of the flame has reduced the water to the state of vapour; the molecules of water press upon all parts of the interior of the ball which imprisons them, like an infinite number of little springs bent against the interior surface of the vessel; but as yet there can be no motion, because all these pressures counteract each other, some tending to push the ball in one direction, others to produce a movement exactly equal in the opposite direction. The resistance of the cork, however, being less than that of the rest of the envelope, it is presently overcome, and the pressure it sus-

tained has ceased to counteract the similar pressure exerted on the opposite interior surface of the ball. The moment this occurs, the backward pressure, so to call it, makes the carriage recoil, whilst the forward pressure throws out the cork.

The same phenomenon occurs when a bullet is fired from a gun in shooting; the butt end of the gun rests firmly against the shoulder, so as to resist the recoiling force. The gases developed in the barrel of the weapon by the combustion of the powder (of which we have spoken in a previous section), act like the vapour in our last experiment. In both cases there is a mechanical effect produced by the action of heat. Therefore heat is capable of developing mechanical force, to overcome resistances, and set masses in motion. This is the starting-point with all machines which are moved by the agency of fire; they work by consuming coal, or any other combustible—that is to say, by the expenditure of heat. As very considerable progress has been made in this branch of applied science during the last few years, it will not be unprofitable to bestow a few minutes on its more careful consideration. Some fire-machines are moved by the vapour of water, others by air; we shall select one of the latter to establish our principle, because the reasoning will be more simple.

Very remarkable experiments have been made with the hot-air engine by M. Hirn, of Colmar, and they have completely solved the problem. We have no need to transport ourselves to the actual locality of this great establishment, where the labours of the engineer keep pace with the progress of science. An ingenious air-engine, recently invented by M. Laubereau, will serve for an example on a small scale. It will be found to deserve our most serious attention, as exemplifying a discovery for which we are indebted to the labours of many great minds, and which in a very few years has produced a revolution in the physical and mechanical sciences. The triumphs of human intelligence are seldom, if ever, of instantaneous achievement. It is only by the exercise of patience, and as a reward of our repeated efforts, that we are permitted to lift the veil of

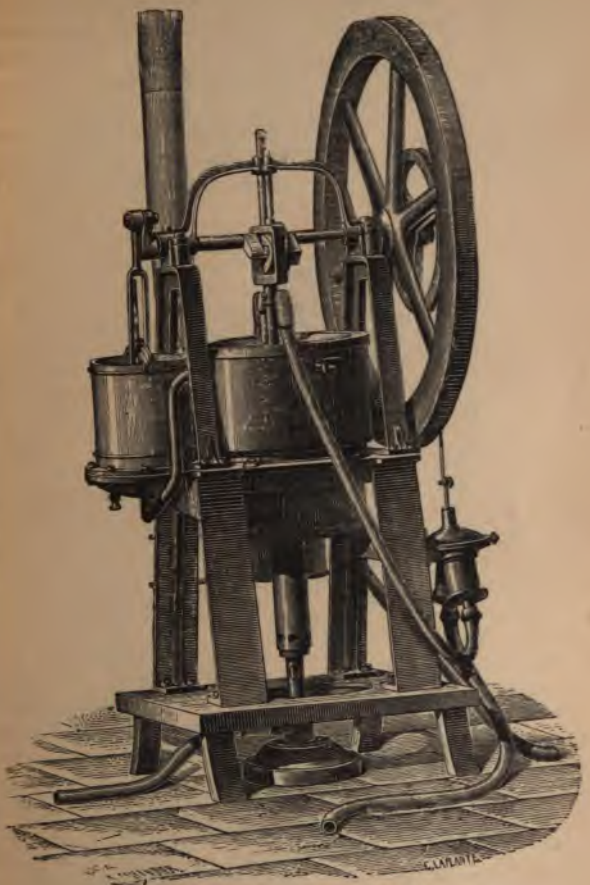

FIG. 2.—Laubereau's Hot-Air Engine.

truth. But what more legitimate subject of pride than the success which awaits such endeavours at last?

10. *A fire-machine spends Heat in effecting work.*

We propose to place our air-machine in a large box, entirely surrounded with ice, as by this arrangement a machine of very small size will suffice for the experiment. In figures 2 and 2 *a* it is represented in perspective and in

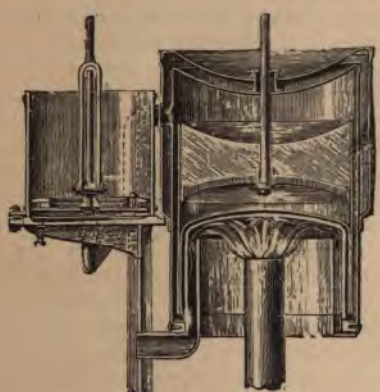

FIG. 2 *a*.—Section of the same Engine.

section. Two vertical copper cylinders are united by a pipe. The piston of the smaller one, alternately rising and falling, turns the spindle or axletree of the machine. On this axle is adjusted the fly-wheel which serves to regulate the rotatory movement, and a roller (not represented in the engraving), upon which a cord is wound, from which depends a weight. The work of the machine, used as a model, is to raise this weight; but in actual business, a pulley and strap are provided, by which the motion of the machine is transferred to the tool. The work effected by the tool is computed as being equivalent to raising a weight to a certain height, and it is customary to multiply the

weight raised by the height, in order to measure the work. For example, a unit of work is the elevation of one kilogramme to the height of one metre. Ten times this amount of work would be to raise ten kilogrammes to the height of one metre, or, what would be the same thing, one kilogramme to the height of ten metres, and so on. Hence a kilogrammetre is called the unit of work.

Let us now see how the action of heat determines the movement of the piston.

The larger of the two cylinders is completely closed. Its lower extremity is extended in the form of a bell, so that it may be heated with coals placed on a grate, or with any other combustible. In the engraving a gas-jet serves to heat the cylinder. The upper part has the same form, but it is furnished with a double case, so that a current of cold water passing between the two cases may prevent this part from getting hot. This current of water is formed by the simple contrivance of a pump, which the axle of the machine sets in motion. The cylinder contains a mass of plaster between two bell-shaped pieces of metal which fit exactly to the upper and lower extremities, as the whole thing is raised or lowered. To effect this displacement a handle and connecting-rod is adjusted to the axle, and acts upon the plaster after traversing the double cases through a box stuffed with tow. The position of this handle in relation to that of the piston has been so calculated, that the mass of plaster may be in the upper or lower part just at the right moment.

We have thus a bulk of air confined in the two cylinders, the pressure of which upon the piston is exerted upwards, whilst that of the atmosphere is exerted downwards. It is understood that the piston rises when interior pressure is greater than the exterior pressure, and falls when it is less. It is the action of the fire and the current of cold water which effects these changes of pressure. To obtain a perfect conception of this action, suppose, to begin with, that the mass of plaster is in contact with the refrigerator; the heat of the fire warms the air of the machine, augments its elastic force, and the piston mounts. When it has arrived

at the proper point in its course, a second period commences; the plaster begins to approach the heated portion, and as it conducts heat badly, and therefore does not allow it to pass by it, the furnace ceases to act on the air; this cools by giving up its heat to the cold water, its elastic force diminishes, and the piston descends, partly in consequence of the impulsion transmitted to it by the fly-wheel, and partly because the atmospheric pressure is now greater than that of the air contained in the machine. Then the plaster again rises; the heat of the fire acts freely on the air, re-heats it, and the motion continues by the simple displacement of the mass of plaster, which acts somewhat in the manner of a screen, alternately intercepting the action of the fire and that of the refrigerator, and the bell-like form of which serves to isolate the interior air as much as possible—first from contact with the cold surface, then from that of the hot surface. The mechanism being understood, we shall now proceed to our experiment.

This little machine, with its furnace lighted ready for action, is placed in the box surrounded with ice, with which the reader will remember we were prepared at the beginning. The charcoal has been weighed, and we secure the dryness of the ice by opening a stopcock, through which any water produced by fusion may run out. Openings conveniently disposed permit the entrance of air sufficient to make the charcoal burn, and the gases developed by the combustion escape by the chimney, after having traversed a serpentine tube plunged in the ice, in order to be thoroughly cooled. The machine is put in at rest, and while this is so the fire has no other effect than to melt the ice. At the end of a certain time, we ascertain on the one hand the weight of the remaining charcoal, and, by subtracting it from that we obtained before the experiment commenced, we find the weight of charcoal consumed, and this number serves to measure the quantity of heat developed by the combustion. On the other hand, we collect the water which results from the melting of the ice, and ascertain its weight, which is evidently proportional to the quantity of heat developed, and, in consequence, to the weight of charcoal consumed;

so that if, in another experiment similar to the preceding one, we made the operation last so much longer that the ice melted might be double, we should find the charcoal burnt also double. It appears, from numerous experiments of this kind, that a given weight of charcoal may, in burning, be made to melt a quantity of ice about a hundred times greater than itself.

After this first observation, set the machine in motion, and measure, as before, the weight of charcoal consumed and of ice melted; add to this the height to which the weight is raised by the action of the machine, and also the value of this weight. For simplicity's sake, suppose that the weight of charcoal consumed be the same as before, shall we have the same amount of ice melted?

Only a very few years ago a savant to whom this question had been put would, very probably, have answered, Yes, because the quantity of heat developed by the combustion of a given quantity of charcoal is always the same, whether the machine be at rest or in motion, and nobody thought, at that time, there could be any intimate relation between heat and motion. Now we are much better informed, and we know that the quantity of ice melted during the combustion of a given quantity of charcoal is less when the machine works than when it is at rest. If the work effected was to raise 1 kilogramme to the height of about 400 metres, the amount of ice melted would be about 12 grammes less; if the work was to raise 2 kilogrammes to the same height, the amount would be 24 grammes less: thus the loss is known to be proportional to the work done by the machine.

From these two comparative observations it is concluded that heat may disappear or be *expended* at the same time that a certain amount of mechanical work *is effected;* that is to say, a certain measure of resistance is overcome by the material system in which this disappearance takes place. We must, therefore, add to our list of the phenomena of heat the mechanical effects produced by it. We have seen it employed in changing the volume of bodies, afterwards infusing solids and vaporizing liquids; further, it can be

employed as a motive power. In the latter case none of the preceding effects will be observed to reveal its presence. When these effects only are taken into account, we say that the heat employed to set the mechanism working has disappeared; but we know that nothing in reality can be annihilated. Mere matter is incapable of moving itself; it can only obey the laws which reign in the universe. The elevation of a weight effected in our experiment is a motion equivalent to another motion which we call heat, which is hidden from our sight, but which we can conceive by calling our intelligence to the assistance of our senses. The task is a long and difficult one, and, before seeking to trace effects to their causes, it is necessary to know those effects accurately. To place them clearly before the reader is the object of this work.

After the experiment we have just described, the problem which follows cannot be difficult to solve, and it will open out to our contemplation a new horizon.

11. *Relation between animal Heat and mechanical work.*

A man is placed in a box in such a manner that the quantity of natural heat disengaged from his body, and the quantity of oxygen he takes in from the air for respiration, may both be measured. Question—Will he disengage the same quantity of heat for the same quantity of oxygen consumed if he remain at rest, as if he does some mechanical work, such as raising a weight by a rope passing over a roller?

The reader is of course aware that respiration is a function of our organization designed to effect the introduction of atmospheric oxygen into the blood. This oxygen causes a slow combustion in our bodies, and in consequence an incessant production of heat. The quantity of heat really brought into play may be measured by the data afforded by the amount of oxygen consumed. Now, if a certain amount of mechanical work is effected, a part of the heat employed is definitively expended for this effect, and cannot serve to heat other bodies. This is proved by the fact that we find a deficit proportional to the work effected,

when we compare the quantity of heat employed to heat the surrounding substances and the quantity which the body has furnished. Thus a man will act like a fire-machine, and the result of the experiment will be the same in both cases. Whilst consuming the same quantity of oxygen, he will disengage less heat if at work than if he be at rest.

This experiment has been tried by M. Hirn upon himself and upon several individuals of different ages and of both sexes: all the data he has thus obtained conspire to the same result.

It is necessary to guard ourselves against the supposition that the disappearance of heat occasioned by mechanical work is necessarily accompanied by a cooling of the body. A little brisk work in general warms the body, and in this state it disengages more heat than when in a state of repose. But it also consumes more oxygen, so that our principle remains unaffected by this well known fact. It is for this reason necessary that the man who does manual labour should have a greater volume of air to respire than the student. The workshop must therefore be commodious and well ventilated, care being taken that there are never too many individuals assembled in a given space, if we wish them to work satisfactorily, and preserve their health. And let us add further that their food should be good and abundant, so that they may be in the right condition to effect work. In fact, as the oxygen of the air serves as the agent of combustion in our blood, so the food we digest furnishes the combustible elements. If insufficient, the air becomes useless: the blood which circulates in all parts of the body will take the substance itself of the tissues, and draw it into contact with the oxygen, which burns it. The body then becomes lean, as it is principally formed of carbon and hydrogen; and as these two substances constitute, with oxygen, carbonic acid gas and vapour of water, it may be said that by the want of food the body of an animal slowly consumes itself, so as to leave what may be called a little cinder only. The foods specially adapted to produce animal heat are saccharine and spirituous matters, because carbon and hydrogen predominate in them. This is the reason why men who work

hard find support from alcoholic liquors. It is surely unnecessary to add that such means should be resorted to wisely and temperately; the bad effect produced on the organization by the abuse, to which workmen are so often tempted, destroys all the good that would arise from their use in moderation.

By these considerations, we are led to regard men and animals as machines, which effect work with the aid of their muscles, by spending heat, exactly like fire-machines. The will determines the motion, and maintains it, provided that the machine is able to consume in its muscles as much heat as is proportional to the work effected. Here, however, we are constrained to admire the superiority of living beings over machines. When a steam-engine or an air-engine works, the whole of the heat which is developed in its furnace cannot be employed with mechanical effect: a considerable part serves to warm the neighbouring bodies. In fact, this lost heat is nearly twenty times the amount of that which we estimate as being effective. Suppose, for example, the mechanical work effected by such a machine to consist in the elevation of 65 kil. to the height of 4,800 metres; 1,835 grammes of carbon must be burned under the boiler. The weight we have chosen is that of an ordinary man, and the height, that of Mont Blanc. When a traveller ascends this mountain, he raises his own weight, and effects with his muscular power the work we have just estimated. Starting from Chamounix in the morning, he would pass the night at the Grands Mulets, start again next morning, and arrive at the summit towards evening: he is at Chamounix on the return journey towards the fall of night. The excursion lasts about 28 hours; but the actual walking, consequently the production of work, lasts only 17 hours. According to M. Hirn, a robust man who ascends Mont Blanc thus consumes 132 grammes of oxygen per hour, which amounts to 2,244 grammes in 17 hours. The combustion taking place in his body is equal to that of 833 grammes of charcoal. Comparing this quantity with that consumed by our steam-engine, it will be seen that it is less than the half.

12. *Electricity produced by Heat.*

The part played by heat does not terminate here. It is capable of producing electricity under its two principal forms. In the seventeenth century, travellers brought from the isle of Ceylon some little green stones, in the form of prismatic needles, which, by heating, acquired the property of attracting light substances. The natives of the country called these stones *Tournamal* (ash-drawers), because, when placed on hot ashes, they attracted them. This name has been corrupted into Tourmaline. We now obtain tourmalines from various localities; those from Brazil, which are green or blue, are the best for experimental purposes. Fig. 3 shows the arrangement adopted by the celebrated Haüy. The tourmaline being made hot, is placed on a little support, balanced with two metallic balls, so that it may remain horizontal when set on a point. If now a piece of rod glass, well rubbed, is presented to the extremities of the stone, it will be observed that one extremity is attracted, whilst the other is repelled; an effect which is attributed to electricity. The tourmaline, therefore, becomes electrical by warming.

FIG. 3.—Haüy's Tourmaline Apparatus.

Since 1821, another method of producing electricity by heat has been known. It is under the form of a current, and this property of heat is often utilized for the purpose of studying some of its properties, particularly radiation. Prepare some little bars of two different metals, such as iron and copper, and solder them alternately by their extremities in such a way that each joint shall be between iron and copper, and the paired joints be all kept in one line, as fig. 4. Unite the extremities of this simple con-

struction by a copper wire, and you will have constructed an instrument called a *thermo-electric pile* (fig. 4.) To make

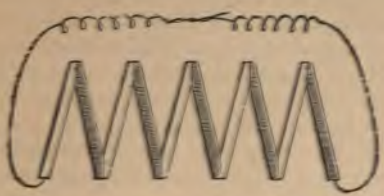

FIG. 4.—Thermo-electric Pile.

FIG. 5.—Pile and Galvanometer.

CHAPTER II.

ON THE EXPERIMENTAL METHOD AND THE THERMOMETER.

1. *Aim of physics.*

THERE are two methods of arriving at a knowledge of the laws of heat,—the one used by philosophers, the other by physicists. The former rely on metaphysical considerations—on certain general ideas relative to the constitution of the universe; and, having laid down a series of rational principles, they proceed to predicate the phenomena which ought to result from them, reasoning from cause to effect. The physicist, on the contrary, first applies his attention to the exact observation of phenomena; he will measure, he will count, he will weigh what he has before him, so as to become well acquainted with its various numerical relations; he will conceive experiments in which the quantities to be measured are plainly separated; he will invent instruments with which he will effect exact measures; and, when he shall have worked out the result of his researches with the precision of a mathematical statement, he will feel satisfied that he has found the laws of the phenomena,—in other words, the method of nature.

For example: a leaden ball suspended by a long string to a fixed support naturally oscillates when it is let go, and we can easily count the number of oscillations it makes in a minute. Now shorten the string, reducing its length to a quarter of what it was; count the oscillations again: we shall find that they are double in number during the same time. If the length be again reduced to a ninth part, the

number of oscillations will be found tripled. The phenomena may be represented by a mathematical statement, whatever be the lengths compared: this statement expresses the law of oscillations.

When by following this method a great number of laws have been obtained relating to phenomena evidently due to the same cause, we may try to trace the effects to their causes; but in doing this we leave the true scientific path, and the conceptions to which we attain are always uncertain. The degree of probability to which they may lay claim depends on the number and exactitude of the observations which led up to them; they are called hypotheses, and are not necessary for the attainment of a knowledge of nature.

In glancing over the history of the sciences, we shall find that the experimental method is of recent origin. The ancients worked metaphysically: Aristotle is the most celebrated master in this school. His doctrine is based on a crowd of nominal distinctions, in which are considered the qualities of things only, and not their quantities. Imagination effected everything. And yet it was Aristotle's logic which prevailed in the schools so late as the sixteenth century. The celebrated Descartes, who lived from 1596 to 1650, himself contributed to retard the progress of the natural method. "Before seeking the laws of weight," said he, "I must learn what weight is; because causes ought to explain effects." So far was he from being in the track which has led to so many surprising and useful discoveries in recent times.

Galileo, who taught publicly in Florence about this time, should be looked upon as the founder of the natural method. He has given its theory, and he has put it in practice, inventing the instruments and conceiving the experiments. "We cannot," said he, "know the essence of things: the absolute escapes us; we can only appreciate the relative. The causes are of little consequence; it is the necessary relations or laws of things which must be discovered." And he discovered the rotation of the earth, the oscillation of the pendulum, the weight of the air, the fall of bodies; he created mechanics, or physics, properly

so called. He was a mathematician, and he knew how to read in the book of nature—a book written, as he said, in mathematical language. And yet it must not be supposed that all his science was hidden in formulæ accessible only to a small number of adepts. Galileo had the great merit of rendering science popular. He once wrote to a friend,—"I have remarked that many of the young men who frequent our universities to prepare themselves for the liberal professions, often show very little taste and aptitude for the study of natural philosophy. Others, on the contrary, whose brains are more happily constituted in this respect, give themselves up to industrial or domestic occupations, without inclining to philosophize, because they imagine philosophy is contained in great books written in *os* and *us*, which they are not able to read. Ah! how I wish they knew that the same bountiful Nature has given eyes to them, as well as to the readers of Greek and Latin, to behold her works, and brains to know and comprehend them."

Let us be disciples of Galileo; let us properly observe and analyze, and thus learn to distinguish the law of phenomena from the hypothesis which pretends to reveal its cause. For us to explain a phenomenon is to describe it, showing the relation which exists between its various parts, or between it and other phenomena already understood. We shall be sufficiently acquainted with heat, when, having become habituated to grasp a natural tie between its several effects, we are able to say which of them will be produced under such and such circumstances.

As to the intimate nature of heat, we are reduced to simple conjectures; and, when one reviews the opinions which have been expressed on this subject, it is easy to see what errors their authors have been led into for want of exact observation.

2. *Hypotheses as to the nature of Heat.*

Until the commencement of the present century the most universally accepted hypothesis was that of the materiality of heat. According to this hypothesis, heat was a kind of fluid matter without weight, different from that which con-

stitutes the molecules of bodies interposed between them and capable of passing from one body into another with great quickness; it was called caloric. A body being warmed was supposed to receive from without a certain quantity of caloric, which added itself to the caloric already contained in the body; when cooled, the caloric, on the contrary, was supposed to be given out.

In combustion the different substances were supposed to combine whilst disengaging caloric, because their molecules, having changed position, constituted a new body incapable of containing the sum of the quantity of caloric contained in the substances previous to combustion. The quantity of fluid contained in the unity of weight of a given body was hence called its *specific heat*. For example, carbon in combining with oxygen disengaged heat, because the specific heat of carbonic acid gas thus formed is less than the sum of the original quantities of heat contained in the carbon and oxygen which constitute the unity of weight of carbonic acid. A few simple observations will prove the error of this hypothesis.

When a piece of copper is filed, heat is disengaged; therefore, according to the preceding theory, the filings should possess a specific heat less than compact copper. But this is not so. Copper filings, when submitted to the action of heat, behave precisely like copper in the lump.

Take another example: If two pieces of ice be rubbed together, and every imaginable precaution be taken against warming them by contact with other substances, the ice will melt as if put near the fire. The partisans of the material theory of heat will say that the specific heat of water is less than that of ice, and, in consequence, friction determines the escape of heat. The water can no longer maintain the solid state, but becomes liquid. Without troubling ourselves with the assumption that heat escapes through friction, the hypothesis is confuted by the fact that the specific heat of ice is less than that of water, contrary to the foregoing argument.

In the first chapter we have described an experiment in which heat disappeared, and yet was not to be found again

in the various bodies in play; such a result could not be conceived if it be admitted that heat is a kind of matter.

This hypothesis is now rejected because a great number of facts have been discovered with which it is incompatible; but, as it has for a long time reigned in science, many expressions and forms of reasoning are still found which carry its mark: so that one must not attribute to them the meaning that they had when first brought into use.

A second hypothesis regards heat as a motion of the molecules of bodies, which is accelerated during warming, and retarded during cooling, which moreover can be transmitted from one body to another in the same manner that the agitation excited at one point of a mass of water is progressively communicated to the whole body by a sort of radiation in every direction. The molecules are supposed to be distributed under the dominion of a universal attractive force, in the midst of a very elastic fluid called ether, which is spread through all space; and it is through the mediation of this fluid that the radiation of heat and light takes place. Thus, when two bodies are brought together, the motion of their molecules tends to distribute itself equally, and the effects of heat would be due to the reciprocal transmission of these motions. Friction develops heat, because, according to this theory, a motion is communicated between the rubbing body and the insensible molecules of the body rubbed. This motion escapes our notice, as do the molecules themselves, in consequence of its extreme minuteness; but our senses are impressed by the various effects of this motion which we call heat. It must be remarked here that the one word heat is employed in two different senses. Here we speak of the effect; elsewhere the same word may designate the cause. A little attention will always distinguish which signification must be accepted under given circumstances.

The disappearance of heat would simply mean the diminution of the motion of the molecules, this being transmitted, not to the molecules of the neighbouring bodies, but to their appreciable masses, which are always put in motion when this disappearance takes place. The molecular motion,

efore, would be converted into the motion of the mass; heat would be transformed into mechanical work, the ne as in the inverse case; in friction and in other circumnces the motion of the mass would be converted into olecular motions, the mechanical work transformed into eat.

This hypothesis, which is called dynamic, has been adopted y a great number of philosophers since the seventeenth century. Indications of it are to be found in the writings of Descartes, Bacon, Euler, and others; but without the precision which it has since attained. It was not until after the time of Galileo, when physics was really founded on experiment, that the metaphysical conceptions took a determinate form, and became capable of serving usefully as the basis of a theory. But in fact it is not sufficient that this hypothesis should be definitely traced out that heat should be spoken of as a motion; it is still necessary to say what kind of motion is imagined, and what are its laws. Until this is done, only the preparation or rough draft of a theory is made out.

Several modern authors have essayed to attain this end, and have presented a theory of heat founded on the dynamic hypothesis. Imagining a peculiar constitution of bodies, they have established formulæ representing the laws which they supposed to regulate the motion of the molecules, and from these they have drawn all the mathematical conclusions possible. To make the theory acceptable, it is necessary that all these conclusions be confirmed by experiment. If a single one is in opposition to the facts, the whole theory must be built up again; the edifice so arduously constructed must be destroyed; and, after having corrected the starting-point, the concatenation of conclusions must be recommenced in order to submit it to a new proof.

Such a labour is a speculation of the mind; certain men of rare genius give themselves up to this, to satisfy their insatiable thirst for knowledge; they contribute largely to the progress of physics by enlarging the field for discovery. In fact, very often a mathematical conclusion leads to the conjecture of a phenomenon until then unknown. The

physicist applies himself to the task; he collects the materials for the new experiment; he observes, and, if the phenomena appear such as he was forewarned, the theory is confirmed. However this may be, a theory established in this manner is always unstable, like every other production of the imagination. Let an adverse experiment be made, and it is overthrown. Newton's theory of light has been destroyed by the disciples of Galileo, and that of Fresnel, conformable to the results of experiment, has replaced it. Only the law of phenomena established by careful observation can rest immutable. This is the secret stolen from nature; it is the victory of our intelligence, aided by our senses; to it we have devoted all the strength with which the Creator has endowed us.

After these reflections, it is hardly necessary to explain that we propose to consider only the principal effects of heat, to co-ordinate them, and find their laws, without troubling ourselves about causes. To accomplish this completely we require some knowledge of geometry. But, as we must not suppose every one to be acquainted with the elements of mathematics, and as this book is intended for all, we shall be able to give only a simple sketch, or sort of initiation.

3. *Invention of the thermometer.*

Our first requirement is an instrument to measure the effects of heat. That which physicists have adopted is called a thermometer. It has many forms, but its essential character is to indicate by the changing volume of the substance which constitutes it, whether the space it occupies may be warming or cooling.

The first thermometer appears to have been constructed by Galileo in 1597. It depended on the dilatability of the air. A glass bulb was joined to the extremity of a glass tube, and a little column of liquid introduced into the tube by the open extremity (A, fig. 6). By this simple means, a small volume of air was imprisoned in the instrument, and this air being separated from the atmosphere by the little mn of liquid, its quantity always remained the same. ' *an instrument* thus constructed is put in a warm

the liquid index increases its distance from the bulb, shows that the air contained gets warmer, and ents in volume, retaining a pressure nearly equal to of the atmosphere, which acts on the index by the extremity of the tube.

ersely, when the thermometer is put in a colder place, olumn of water sinks—that is to say, the index ap- hes nearer to the bulb, because the contained air is l and reduced in volume.

ny savans in Galileo's time d themselves to the study of ermometer. In fact, the founda- f modern physics was then laid. felt the necessity of creating ments for observing natural mena in a better manner than een yet done. The thermo- of Cornelius Drebbel, son of ch peasant, came rapidly into Flanders and England. This onsisted of a glass bulb and B, fig. 6), containing air; the placed vertically, and its open ity plunged under some liquid ned in a little dish. To re- the quantity of air which l remain in the bulb, it is ed, which causes several bub- f air to escape; after this, it wed to cool. The liquid then rises in the tube, and its serves as an index, like that of Galileo's thermometer. e first spirit thermometer was constructed in the tine Academy. The reservoir has the same form as ; it is still a glass bulb or cylinder, joined to the ity of a very narrow glass tube; but it contains spirit d of air. To replace the air naturally contained in it is liquid, an artifice is necessary. The bulb is held fire whilst the end is plunged under the spirit. The air ed in the *bulb dilates,* and bubbles through the liquid

FIG. 6.—Air Thermometers.

whilst it (the air) is warmed. The source of heat is removed; when the air contained in the instrument cools, and contracts, and the liquid rises into the bulb, which it nearly fills. To remove the remainder of the air contained in the bulb, it is again put over the fire, so as to make the alcohol boil. Its vapour mixes with the air, and, rushing out in a jet, they escape together. At this moment the open extremity of the tube is quickly plunged into the alcohol, and the heating discontinued. In the process of cooling, the alcoholic vapour which fills the bulb condenses, ultimately occupying but a very small space; so that the pressure of the atmosphere causes the liquid contained in the dish to rise quickly into the bulb. This time it will be entirely filled. Yet there is always a small bubble of air which it is necessary to remove. To effect this, before removing the dish of alcohol, the instrument must be allowed to cool thoroughly; a string is then attached to the tube, and it is swung rapidly with the bulb outwards, like a swing. By this motion the heaviest particles remove themselves farthest from the centre; the alcohol contained in the tube enters the bulb, and the bubble of air contained in the bulb approaches the operator's end, and consequently can be completely removed from the liquid. When this is completed, the instrument is in the state represented by fig. 7. To regulate the quantity of alcohol which should remain, the bulb must be warmed a little; the alcohol then expands, and several drops escape by the opening. It is allowed to cool; the alcohol contracts, and its level will be found nearer the bulb than before. This manœuvre is repeated, if necessary, until its level is found to be about a third of the length of the tube, measuring from the bulb.

FIG. 7. Alcohol Thermometer.

To finish the construction of the thermometer, it is only necessary to direct a blow-pipe flame on the end of the tube; the glass softens, and the opening can be closed by

drawing it out. There now remains some air confined above the level, having no communication with the atmosphere. When the bulb is warmed, the alcohol expands, its surface presses on this air, compresses it, and augments its elastic force; this is the reason that the alcohol does not vaporize, and that it can be heated somewhat considerably without being seen to boil. An explanation of this phenomenon will be given further on (Chapter VIII). Ordinarily the alcohol is coloured red, that the movements of its level may be more readily followed.

The spirit thermometer offers several essential advantages over those of Galileo and Drebbel; as, owing to its being shut, the atmosphere has no effect on the bulk of the alcohol; whilst in the other two, which are open, the atmosphere exerts pressure on the index, which varies as its pressure changes while there may be neither warming nor cooling. What we have to observe on the whole is, that the displacement of the *index* in these two instruments is produced by heat and by atmospheric pressure, and that it is difficult to discern the specific effect due to each of these causes.

About 1680, mercury began to be used in place of alcohol, and it was found to possess great advantages. Mercury may be made hot or cold quicker than alcohol: as it is opaque, it may be very easily seen in the tube, even when this has an interior diameter excessively small, which condition renders the instrument more sensitive. It is also easier to obtain mercury perfectly pure. In fine, mercury may be heated to a much greater degree than alcohol, without being transformed into vapour.

A mercurial thermometer may be constructed in the same manner as the spirit instrument, except that there is no bubble of air to remove by the swinging motion, and it is not necessary to allow the tube to remain full of air. When the necessary quantity of mercury has been introduced into the instrument, so that its level may be about a third of the whole length, reckoning from the bulb, the latter is heated until the mercury reaches the opening, which is then immediately closed with the blow-pipe. By this means air is

altogether excluded; and when by cooling the level has again nearly reached the bulb, there is a perfect vacuum in the upper portion of the tube.

So far as we have just constructed it, the thermometer will perfectly indicate, by the displacement of its level, whether there be a warming or cooling action going on; but as yet it does not exactly *measure* the effect of the heat. To do this it must now be graduated.

4. *Graduation and use of the thermometer.*

It is since the year 1741 that the plan for graduating thermometers adopted by the Swedish physicist, Celsius, has been followed. Until then, there had been no fixed plan, and the numbers indicated by various thermometers did not accord together.

On the whole length of the tube of the thermometer a scale of equal divisions is marked; each division is called a thermometric degree, and these degrees are marked by consecutive numbers. This graduation must be made in such a manner that all the thermometers placed in the same circumstances,—for instance, in the same quantity of water,—have their levels stationary, after some time, before the same number on the scale. The plan of Celsius permits the realization of this condition, so that any number of thermometers may be compared together.

According to this plan, the thermometer is allowed to remain immersed in ice, placed in a vessel pierced full of holes, so that the water resulting by liquefaction may run out; when this precaution is taken, the level of the mercury will become stationary. Its place is then marked on the tube. The thermometer is then immersed in the vapour produced by water in full ebullition (fig. 8). The level rises by the expansion of the mercury, and soon becomes stationary. Its place is again marked on the tube. Two fixed points are thus obtained, which serve to regulate the scale.

The thermometer being adjusted, for example, on a small piece of wood, two marks are made opposite the

fixed points, and the figures 0 and 100 are written by their side.* The intervening space is then divided into one hundred equal parts, the division being extended to the

FIG. 8.—Apparatus for graduating the Thermometer.

FIG. 9.—Ordinary Thermometers.

extremities of the tube. The numbers are the same on either side of zero, as indicated by fig. 9; and to distinguish them, it is only necessary to say that they are above or below zero. This graduation is called the Centigrade, and it is constantly spoken of under that name.

The word *temperature* is adopted to designate the state of

* The graduation here given is that of the Centigrade thermometer. The principle of construction is, of course, the same for any other scale in use.

bodies relatively to heat. When a body is placed in contact with a thermometer, the mercury rises or falls in the tube according as the body is hotter or colder than the thermometer, and its level stops at some division of the scale. The corresponding number represents the temperature of the body.

The thermometer thus serves to indicate the calorific state of bodies. If its level is stationary, the temperature is constant; if it rises or falls, the number of degrees through which it passes are counted, and this number represents the elevation or reduction of the temperature.

FIG. 10.—Brongniart s Pyrometer.

A mercurial thermometer may have a scale extending from 40 degrees below zero to 360 degrees above.* It is only between these two temperatures that mercury remains liquid. At a lower temperature it becomes solid; at a higher it is gaseous, and in consequence it can no longer avail us in the circumstances.

The alcoholic thermometer is employed for measuring excessively low temperatures, because this liquid does not freeze. As for very high temperatures, they are measured by pyrometers, a kind of thermometer dependent on the expansion of solid bodies.

Thus in the manufacture of Sèvres china M. Brongniart has used the thermometer represented in fig. 10 to estimate the high temperature of his furnaces.

* In Fahrenheit's scale from 39° below zero to 680 above.

A plate of porcelain, placed in the oven, carries a bar of iron let into a groove, against the bottom of which one end of the iron bar rests, whilst the other end touches a bar of porcelain which passes through the wall of the furnace. This is pressed against the bar of iron by a lever. When it is heated the iron expands, and also the porcelain, but the lengthening of the latter may be neglected; it is the iron which puts the lever in motion. The movement is transmitted by a ratchet and pinion to a needle so constructed as to traverse the divisions of a dial. By this artifice the changes produced by heat in the length of the bar of iron are easily ascertained.

The scale inscribed on the dial marks 100° and zero (Centigrade) when the bar of iron is placed in boiling water or in melting ice; and the numbers rise to 1,500° because the iron remains solid until it reaches this high temperature. But such a thermometer cannot be compared with the mercurial thermometer, as different numbers are nearly always indicated by the two instruments when placed in the same circumstances.

Physicists use, for precise experiments, air thermometers having some analogy with that of Galileo; but it would be a digression to describe them more particularly.

Having the thermometer, then, we are provided with a very delicate instrument, which will enable us to observe the phenomena of heat, much as the telescope enables the astronomer to observe celestial phenomena. In any experiment relative to heat we shall have to follow the displacement of the index, in order to note temperatures.

5. *The measurement of Heat.*

Our first application of the thermometer is for the purpose of fixing the unity of heat.

As explained in our first chapter, we are able to measure the quantity of heat that a body disengages by the weight of ice that it is capable of melting. Evidently, to melt two kilogrammes of ice, twice the quantity of heat is wanted than is necessary to melt one. But such a unit is not

CHAPTER III.

SOURCES OF HEAT.

1. *Solar Heat.—Terrestrial Heat.*

ANY given body is called a source of heat when heat disengages from it, and the loss is at each instant repaired by a new production.

The sun is the most beautiful and the most abundant of the sources of heat of which we are able to make use. M. Pouillet has invented an instrument with which he has measured the quantity of heat emitted by this body. It is a thermometer, the reservoir of which is inclosed in a very thin silver box, filled with water (fig. 11). The tube of the thermometer projects from the box by one of its surfaces, and it is inclosed in a copper tube, provided with a groove. so that the graduation may be visible. The other surface of the box is blackened with smoke; this face should be exactly perpendicular to the direction of the tube. The instrument is exposed to the sun when there are no clouds to intercept its rays, and the box is turned in such a manner that the black face receives the solar rays perpendicularly. The rise in temperature is observed during five minutes, and a certain number of degrees thus obtained. The number of thermal units necessary to make the thermometer rise one degree being previously determined, a simple multiplication will give the additional number of such units gained by the instrument during its five minutes' exposure to the sun. To ascertain the real amount of heat that has reached the black surface, the preceding number must have added to it the heat that the

apparatus loses during five minutes by its own radiation towards the sky; for it is known that the celestial space exerts a cooling action on terrestrial objects. The exact amount of heat to be added is obtained by making in the dark another observation analogous to the preceding.

But the whole amount of heat emanating from the sun is not yet ascertained, as some portion of it has been absorbed by the atmosphere. M. Pouillet has estimated this proportion by combining a great number of observations, and he has thus been able to calculate the quantity of heat that reaches the earth in one year. It is so great that ordinary figures would fail to convey an adequate idea of it. It must suffice to observe that it is capable of melting a mass of ice sufficient to envelope the globe to the depth of 30 metres (about 100 feet). Only one-half of this immense quantity of heat reaches the surface of the soil in consequence of absorption of the other moiety by the atmosphere.

FIG. 11.—Pyrheliometer.

If we now wish to know the total quantity of heat emitted by the sun, not only towards our planet, but in all directions at once, an empty sphere must be conceived, the centre of which is the sun, while its surface is drawn through the centre of the earth. Astronomy teaches us that 2,300 millions of globes, as large as our earth, placed one against another, would be required to cover entirely this imaginary sphere. It follows that the whole quantity of heat emitted by the sun is 2,300 million times that which reaches our earth, and which we have just estimated.

to examine the result of the combustion of carbon in oxygen.

Instead of the phosphorus in the former experiment, put a piece of red-hot charcoal in a porcelain capsule, and immerse it in a bottle filled with oxygen. The charcoal now burns briskly; and when it has ceased burning, it will be easy to prove that the gas contained in the bottle is no longer oxygen, and that the piece of charcoal has diminished in weight. To place this beyond all doubt, introduce into the bottle a small lighted taper, and it will cease to burn, whilst if the bottle had contained oxygen it would burn with more activity than in the air. This is due to the fact that the charcoal has combined with the oxygen contained in the bottle, and produced a new substance called carbonic acid gas. It is transparent and colourless, like air or oxygen, but it does not support combustion, a character which suffices to distinguish it. When carbon burns in our grates, the same chemical phenomena occur: the oxygen is provided by the air, and the carbonic acid is carried up the chimney by the gaseous current. This current is formed of this gas mixed with vapour of water, with nitrogen, which does not combine with carbon, and with smoke or finely divided carbon, of which the pulverulent particles are deposited on the sides of the chimney, and there remain as soot. Smoke would not be formed if the oxygen was supplied to the fire in sufficient quantity, because all the carbon would burn: it indicates, therefore, an incomplete combustion. We remain contented with this, because we could

FIG. 12.—Combustion of Phosphorus in Chlorine.

not provide for complete combustion without adopting chimneys of a too costly construction. As to the ash from the fire, it is formed by the earthy substances which are mixed with the carbon, and which do not combine with oxygen.

Carbon is charcoal in its state of greatest purity. Such is plumbago, commonly known under the name of black lead. Above all such is the diamond, most beautiful of all the precious stones, which is found in certain sands of the Indies and Brazil. The finest diamond in the French crown weighs scarcely twenty-eight grammes, and it is worth twelve millions of francs. It is known as the Regent Diamond, having been bought during the regency of the Duc d'Orléans. If this magnificent jewel were to be placed in oxygen, after having been heated to redness, it would burn away completely, consuming about 52 litres (nearly 11½ gallons) of oxygen, and producing about the same bulk of carbonic acid gas.

The quantity of heat disengaged by the combustion of carbon is known, whether it be in the state of charcoal or in the state of diamond, because in both cases it is the same.

One kilogramme of carbon, in whatever form, produces by burning in oxygen 8,000 thermal units, a quantity of heat capable of melting 100 kilogrammes of ice. This estimation will serve as a new illustration of the immense quantity of heat furnished by the sun. If the sun were covered with a bed of carbon burning in oxygen, and having a thickness of 27 kilometres (nearly 17 miles), the heat emitted by this gigantic conflagration would be equal to that really given out by the sun in one year.

If we suppose the solar heat to be really due to such a conflagration, the sun being a globe of carbon, it would be entirely consumed in 5,000 years. As it has not changed in size or in magnificence since the creation of man, this hypothesis must be rejected.

The convenient property of coal gas to burn in air has furnished us with a source of heat (and light), of which we have largely availed ourselves. The coal being heated in close retorts, a gas is produced, which passes by means of

pipes into an enormous reservoir, from which it is afterwards directed by subterranean channels to the various quarters of the town. Each gas-jet is adjusted to the end of a branch pipe from one of these channels, and a stop-cock closes it when it is not required to burn. When this tap is opened, a jet of gas escapes from the burner, consisting of carbon and hydrogen in combination. A little excess of pressure maintained in the gas reservoir, is sufficient to produce this jet. When a lighted match is brought near the jet, it is heated, the carbon separating from the hydrogen; the latter having a very great affinity, for atmospheric oxygen combines with it to form water in a state of vapour; the carbon having a somewhat less affinity for oxygen combines next to produce carbonic acid gas. These two combinations produce so much heat, that a flame is kindled; this flame continues to heat the gas as it escapes from the burner. This gas burns in its turn, and thus the flame is maintained at the same intensity so long as the supply of gas continues.

FIG. 13. Gas Flame

Let us examine the details of this combustion; we shall receive some interesting and useful lessons.

The flame has the form represented in figure 13, where the jet comes from one end of the straight tube. When the jet of gas escapes from a great number of small holes, as is often the case, the flame consists of an assemblage of many small flames, constituted as we are about to describe.

Hold a piece of paper over our simple flame at the base of the jet, and take it away before it shall have inflamed; we shall see a black circular mark of the outline of the flame. From this we conclude that the centre of the flame is cool, and that there no combination takes place; which is easily explained, when we say that the central parts of the jet are not in contact with air. The surrounding parts

are, on the contrary, very hot; they form an envelope which has left its trace on our paper by carbonising it, and in which the combination with oxygen takes place, because these parts are in contact with the air. This envelope is the luminous part of the flame, and we may notice that it consists of two parts, a fact which will lead us to discover the cause of its light. Present cautiously a very fine metallic wire, and you will observe that it becomes red-hot before reaching the luminous border of the flame. Therefore, there is a first stratum or layer, quite outside, in which the heat is very great; it is in this stratum that the combustion becomes complete. Into the luminous stratum which it covers, the oxygen of the air does not penetrate sufficiently to effect the combustion of the whole of the carbon. The carbon then is set free for a short space; it leaves the hydrogen, which, more mobile than itself, instantly combines with the oxygen of the air, and it is not until a little later, when arrived on the outside of the flame, that it burns in its turn, of course subject to the condition that the air is supplied in sufficient quantity on all sides; if not, it will remain free, and, growing cool, will lose its affinity for oxygen, to maintain which, a high temperature is necessary; in this case it will appear as smoke. It is in its passage from the inner to the outer part of the flame that the carbon, being free for a moment, and at the same time strongly heated by the outer stratum, becomes luminous.

To sum up, there are three parts to be considered in a flame of gas: the dark central part, where there is no combustion, but where the carbon commences to separate from the hydrogen; the luminous stratum, where the carbon is for a moment free and heated to whiteness; lastly, the exterior bluish stratum, which is the hottest, and in which the combustion is completed.

It will now be understood why the form of the burner is of such importance, and also the modification it should undergo, according as it is required to supply light or heat.

If light be required, it is necessary to preserve the carbon for some instants from the action of the air, and yet not so long that it can become converted into smoke. If, on the

contrary, heat be required, the carbon must be burned as quickly as possible, and not allowed to remain free. The celebrated German chemist, Bunsen, keeping these facts in view, has constructed a gas-burner which answers perfectly as a source of heat.

The straight tube from which the gas-jet issues, is fixed in the axis of a wider tube, pierced near its base with a number of small holes (fig. 14). The air, entering by these holes, becomes intimately mixed with the coal gas, and, of course, the proportions of the mixture are regulated by the size of

FIG. 14.—Bunsen's Gas Burner.

FIG. 15.—Candle Flame.

holes. It burns at the upper extremity of the wide tube, as shown in the engraving (fig. 14), with a very pale but nevertheless very hot flame. If the small air-holes be stopped up, the flame will become more luminous, and lose a proportionable amount of heat. This experiment demon-

strates, in the simplest manner, the exactitude of our reasoning.

If the object of this little work was limited to the consideration of heat, what a variety of interesting phenomena would flame furnish us with. Here, for example, is an ordinary taper (fig. 15). Observe the little crater of white wax, in the centre of which rises the blackened wick, and at the same time inclines itself a little on one side. The heat of the flame is continually consuming, and as continually renewing, the supply of melted wax, which is the combustible material. The parts farthest from the wick are the last to be melted; the liquid collects at the base of the wick; it rises by the thousand small interstices of the twisted cotton which forms it. precisely as the coffee which you touch with a lump of sugar spreads immediately over the whole piece, and fills all its pores. This melted wax again is a combination of carbon and hydrogen; heated in contact with air it is reduced to vapour, renewing incessantly the supply of gas round the wick. After this point is reached all happens just as in the preceding experiment. You can distinguish in the flame of the taper the three parts which we have already studied in the gas flame. The wick remains blackened in the central part. Its bent extremity presents a little red-hot point in the exterior envelope; at this point it is submitted to a very high temperature in contact with air, and is consumed entirely, which causes it to shorten as the taper is used. The curve of the wick is determined by the manner in which it is twisted.

Among the numerous curious experiments which have been made with a burning candle, the following will serve to further confirm our theory. Frankland, being in the year 1859 at Chamounix, at the foot of Mont Blanc, weighed six candles, and made them burn for one hour in the town; he weighed them again, and thus measured the loss in weight that they had sustained by the transformation of a certain quantity of the wax into carbonic acid gas and vapour of water, during the combustion. Afterwards, he carried the same candles to the top of the mountain, about 12,000 feet

in height, and again made them burn for an hour, whilst sheltered from the wind under a tent. The combustion seemed very feeble; the flames were pale, and yet, on weighing the candles when returned, it was found that the quantity of wax consumed was nearly equal to that in the experiment at the foot of the mountain. Consequently, the combustion had in both cases an equal energy; only at the top of Mont Blanc the pressure of the air is less by about one-half than it is in the valley. As a consequence, it is much more subtle; it penetrates the flame more easily, and does not leave the carbon free for an instant. In accordance with this, it would be reasonable to suppose that, with a sufficient pressure, the flame of the same candles would become smoky, the compressed air being insufficiently mobile to allow it to enter the flame, and cooling the carbon sufficiently to prevent its burning. Dr Frankland, indeed, proved this to be the case somewhat later.

In this manner an able observer not only explains natural phenomena which present themselves to him, but is also enabled to predicate other new phenomena, by a method of reasoning which is called induction. The verification of a foreseen result is a discovery which extends our knowledge beyond its own immediate bounds, and the joy of the philosopher when he has arrived at the desired end is so great that he soon forgets his fatigue. The celebrated physicist Rumford, referring to an experiment made in 1798, acknowledged frankly that its success filled him with so much childish delight, that he felt it would be well to hide his joy if he was ambitious of the reputation of a grave philosopher.* But the contemplation of the marvels of nature suffices to render a man simple and modest; his pride vanishes in presence of the unfolding grandeur of creation.

Amongst the combustibles in use, hydrogen disengages most heat when combining with oxygen and producing water. With equal weights it disengages a quantity of heat more than four times that disengaged by carbon. It cannot, however, be advantageously employed, as it must be prepared by chemical processes and preserved in very large

* Lessons on Heat, by Mr Tyndall.

reservoirs, it being about thirteen times lighter than air bulk for bulk. Pure oxygen must also be made for this purpose and kept in special reservoirs. It, therefore, is also an expensive agent to be employed in the production of heat, and for this reason it can only be used in certain cases, when the ordinary methods are insufficient. For example, M. Henri Sainte-Claire Deville has arranged the oxy-hydrogen blowpipe in the following manner, for the fusion of platinum, a metal as precious as gold sometimes used for minting, particularly in Russia, and which cannot be melted in an ordinary furnace.

FIG. 16.—Oxy-hydrogen Blowpipe.

The oxygen is supplied by a copper pipe, terminated by a platinum jet; the hydrogen is supplied by a concentric pipe, which incloses the former and of which the extremity is also made of platinum (fig. 16). The gaseous mixture being kindled, burns with an excessively hot, pale-coloured flame. The jet is fixed in a narrow cylindrical hole pierced through a block of quicklime, which is placed like a lid on a vessel of lime. This vessel is pierced with holes at the base, so as to allow the vapour of water, which results from the combustion, to escape; and it incloses a crucible, also made with quicklime, in which the metal is placed. The flame envelopes the crucible on all sides, and the platinum

melts. With five gallons of oxygen and ten gallons of hydrogen, one pound (Troy) of platinum may be melted.

3. *Heat produced by mechanical motion.*

Next to chemical action, mechanical movements offer us the most important means for the production of heat. Mechanical motion, indeed, may be called the one universal source of heat throughout the creation, and from it all other means are derived.

It is hardly possible to imagine a time when the fact that friction produces heat was unknown. Seneca observed that the shepherds procured fire by rubbing the extremity of one piece of hard wood in the cavity of another; and this method is still in general use amongst savage tribes. Pivots in machinery become heated by friction against their cushions; the nave of a wheel often takes fire by rapid turning. It is well known that fires have been caused on railways in this manner; to prevent such accidents some fatty matter has to be interposed between the rubbing surfaces, and it requires to be frequently renewed. When the friction is very violent, there is a rending asunder of the parts, and the heat produced becomes very great. Thus, a steel wheel rubbing against a flint throws out particles of red-hot iron, and attempts have been made to use this method as a source of light for coal mines. When we strike a light with the old-fashioned flint and steel, we act in an analogous manner; the particles of red-hot iron produced by friction and the shock of the stone fall upon the tinder and set it on fire.

The turning of metals offers some remarkable examples of heat produced by friction. In one of Rumford's experiments, a casting intended for a cannon was fixed on the lathe to be bored. A cavity was made at one of its ends, and a blunt borer adjusted, so as to develop intense friction at the bottom of the cavity; afterwards it was surrounded with water. The borer being put in action, hollowed out the piece, and the heat developed by this mechanical operation reduced into vapour nearly nine quarts of water in two

hours and a half. The hammer which strikes a piece of metal on the anvil heats it. A leaden bullet fired against an iron target has been known to melt in the act of striking. Solids, liquids, gases become heated when compressed; physicists have invented several experiments to exhibit this effect of compression. With solid or liquid bodies which are compressible to a small extent only—that is to say, which diminish very little in volume when under great pressure—the production of heat is small. Thus, to elevate the temperature of ordinary ether 6° only (about 10° or 11° Fahr.), it is necessary to exert a pressure of 30 atmospheres—*i.e.*, a pressure thirty times greater than that of the atmosphere.

FIG. 17.—Compressibility of liquids.

To appreciate this illustration, imagine a cylinder (fig. 17) containing a litre of liquid. This cylinder is a square decimetre in size, and in consequence the height of the liquid is one decimetre. The pressure of the atmosphere on the surface is equal to that of a piston weighing 103 kilogrammes. This pressure is transmitted by the liquid to the sides of the cylinder, so that we may say the surface of the ether receives a pressure of 103 kilogrammes for each square decimetre Now place a piston weighing 103 kilogrammes on the surface of the ether; it will be compressed at the same time by the piston and the atmosphere; the total pressure will be 206 kilogrammes, or 2 atmospheres. Further, put on the piston a weight of 103 kilogrammes, the total weight resting on the surface of the ether will be 309 kilogrammes or 3 atmospheres. Suppose this multiplied by ten—*i.e.*, to 3,090 kilogrammes—and you will have the idea of a pressure equal to 30 atmospheres. Well, under these conditions the temperature of the ether will be elevated by 6° C., and the volume of the ether will be diminished by about 4 cubic centimetres.

Gases, above all, become heated by compression, their volume also suffering considerable diminution. The adjoining woodcut (fig. 18) represents an instrument depen-

dent on this property. It consists of a glass cylinder, one extremity of which can be hermetically closed by a screw stopper, internally hollow, and in which also a piston works. To use it, the piston is placed at the open extremity of the cylinder, the stopper is unscrewed, and a piece of tinder put in its cavity. It is then screwed up again, and thus a certain quantity of air is inclosed in the apparatus in contact with the tinder. Now push the piston down sharply; the bulk of this air will become very small, its elastic force very great, and it will spontaneously develop enough heat to make the tinder catch fire. On again opening the stopper, the tinder will be found burning.

Fig. 18. Compression Syringe.

In all these experiments on heat produced by compression, it is necessary to exercise the mechanical effort with considerable quickness, without which the heat developed is communicated to the neighbouring bodies, and its effect is no longer the same. By placing the body to be compressed in a reservoir, made of some material which is a bad conductor of heat, such as glass, and by acting very quickly, the loss is but slight.

4. *Heat produced by mechanical work is equivalent to the work done.*

All the phenomena shown in the above experiments, the form of which may be infinitely varied, are marked by a common character, discovered a few years since, and which it is necessary should be clearly understood. But, first, it is indispensable to have some notion of mechanics.

When a body is at rest, it cannot put itself in motion; it is said to be inert; it must be moved by so[illegible] cause [illegible] is called force. So long as the [illegible] body is subject

to all the changes which depend on the method of action of the force; but if it is suppressed, the body continues to move in a straight line uniformly, without power in itself to change this motion; it shows inevitably, by virtue of the law of inertia, the impulse which the force has given it, and this lasts so long as a new force does not interfere. This is one of the fundamental properties of matter.

It is impossible to find in the universe any body which is not in subjection to some force; because all bodies attract each other, mutually following the law of universal gravitation, and it is this attraction which causes our globe to describe its annual circle round the sun, the moon to turn round our earth, and all the celestial bodies to move in space.

In a great number of cases a body may sometimes appear to act as if no force were acting on it. For example, when we consider its state in relation to ourselves. Thus, a body suspended by a string is really, like ourselves, dragged along by the movement of the earth; but we say that it is at rest, because we abstract in idea this common motion, and thus simplify our reasoning.

The body suspended by the cord is relatively at rest; and yet it is attracted by the earth, and if it does not rush to meet it, it is because the cord holds it. Where, in this experiment, do we find the principle of inertia? The cord is stretched, because the earth attracts the body: the force which stretches the cord is called the weight of the body, which must not be confounded with gravity, the name by which we designate the cause of terrestrial attraction. The cord resists this tension, and this resistance may be said to neutralize the weight. The body is, therefore, submitted to the simultaneous action of two equal but contrary forces which destroy each other, and, in giving this explanation, a simple fact is expressed, such as observation reveals it.

Now cut the cord; its resistance no longer neutralizes the weight: we have thus suppressed one of the two forces; the other remains, that which is due to gravity, and the body falls. Its movement is not uniform, so long as gravity alone actuates it. In the first second, it falls, let us say, through

49 decimetres; three times farther in the second, five times farther in the third, seven times farther in the fourth, and so on. When a body falls there is an expenditure of action, or work done, the exact measure of which is ascertained by multiplying the weight of the body by the distance through which it passes. If it weighs one kilogramme, and it falls from a height of 425 metres, it is said that a work is effected of 425 kilogrammetres; the body has then acquired a certain energy, of which one manifestation is the speed it possesses.

If, by any artifice, the supposed body weighing one kilogramme were freed from the influence of gravity after its fall of 425 metres, the body would, by virtue of its inertia, continue its vertical motion; but in this case, the rate would be uniform, it would travel at about the rate of 91 metres per second. So long as this uniform motion continued, no fresh work would be spent; the energy of the body would remain the same. The number 91 metres, measures its speed after the fall of 425 metres. Suppose that the assumed body weighing one kilogramme were a perfectly elastic ivory ball, and that, after having fallen at the distance of 425 metres, it strikes against a marble slab firmly fixed to the earth; in this case the ball would rebound, and if the slab were perfectly horizontal, it would again rise to nearly the height of 425 metres. Having reached its starting-point, it would remain an instant at rest; and if at this instant gravitation ceased to act upon it, it would remain at rest for an indefinite period. Let us now inquire what really happened when the ball struck against the slab of marble.

The ball has been flattened, and the slab has been slightly depressed at the point of contact. This fact may be demonstrated by rubbing a little grease on the surface of the ball: after the shock, a circular spot will be seen on the slab, indicating that contact has taken place at a great number of points. Now, a spherical ball can only touch a plane in *one point;* therefore the ball has been flattened, and its shape altered by the blow. On the other hand, the surface of the slab has been slightly depressed, but so *very* slightly, that we need not take it into account. This is a

necessary condition to enable the ball to rebound to nearly the same height as that from which it fell. In other words, the marble slab being supposed perfectly inflexible, the flattening of the ball has alone to be considered.

The ball has been progressively flattened while its speed was being annihilated, and at the same moment at which the flattening had become as great as possible, the motion ceased. The ball then resumed its primitive shape, still continuing in contact with the slab, from which it does not separate until it has entirely regained its form. At that moment it rebounds.

As the ball rises, gravitation influences it so as to retard its motion by resistance. There is also the resistance of the air, which acts with the same effect as gravitation; but this is very small, and we may neglect it. When the ball has come to a state of rest, at about the height of 425 metres, the force of the resistance overcome—in other words, the amount of work—has equalled 425 kilogrammetres. Thus the quantity of force developed by the fall of a body is capable of making the same body rise to a height equal to that of its fall; and when this ascent is effected, it is entirely consumed. In general, we shall call *spent* work the effect of a force which makes a body move, and *produced* work the effect of a resistance which is surmounted by a body in movement. In our example, there is a work spent during the fall equal to 425 kilogrammetres, and equivalent work produced during the rise.

The experiment we have just imagined is meant to explain the meaning of *the conservation of force*, which is one of the bases of mechanics.

When a force has acted on a body and has put it in motion, it confers on it a certain energy which measures the work *spent*. The body loses this energy in the act of surmounting resistance, and *produces* work equal to the preceding. It is this fact we have just observed. Very often a body loses its energy in a different way,—namely, by transmitting it to another body, and bringing itself to a state of rest. But then the bodies which have acquired this energy lose it in their turn by an equivalent production of work,

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in the preceding experiment amounts to what it has been agreed to call one thermal unit. The appellation *mechanical equivalent of heat* has been given to the amount of 425 kilogrammetres by M. Mayer, one of the founders of the new theory. If we perform the last experiment with a body of any weight whatsoever, falling into the water from any height, there will be a number of thermal units created equal to the number of times 425 contained in the number of kilogrammetres expended: for example, if the body weighs two kilogrammes, and falls from a height of 850 metres, there will be 1,700 kilogrammetres expended, and four thermal units created.

We have already discussed the mechanical equivalent of heat (end of Chapter II.) in connexion with the subject of the production of work. Here, therefore, it will suffice to express the principle: when heat is made to overcome resistance, one thermal unit disappears, whilst 425 kilogrammetres are produced; and, on the other hand, when heat is created by mechanical motion, one thermal unit appears, whilst 425 kilogrammetres are expended.

The same correlation exists between mechanical work and heat in all the cases in which percussion, fall, friction, or compression develop heat. In all experiments made with the object of measuring this correlation, there are two kinds of observations to make. The first are destined to make known, by calculations based on mechanical laws, the amount of work expended; whilst the others serve to calculate, according to the laws of physics, the amount of heat created.

To take a single example. Two or more plates of copper, fixed to a vertical axis, are completely submerged in water; a string being wound on the axis, passes over a pulley, and is stretched by a weight (fig. 19): a thermometer is placed in the water, and the several weights of the water, the vessel, and the copper plates are known. Thus arranged, the weight is allowed to descend. Gravitation is the motive force, and the work effected (*travail moteur*) can be measured by multiplying the weight by the distance it passes through in descending. The revolving plates agitate the water, and from the friction which takes place results

the disengagement of heat. The rise in temperature is marked by the thermometer, and thus we have all the data necessary to calculate the quantity of heat created. As to the work expended, there are several things to be con-

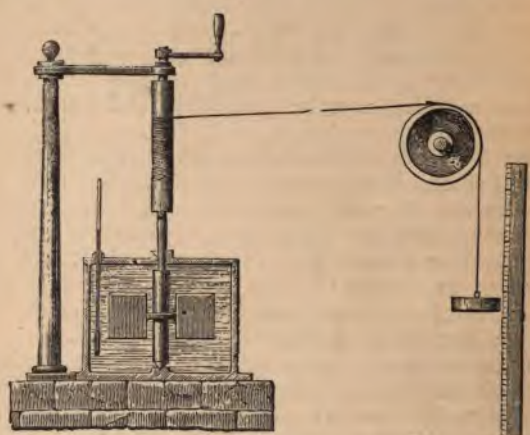

FIG. 13.—Joule's Apparatus for producing heat by the friction of liquids.

sidered. As the descending weight is stopped on reaching the earth, it might be thought sufficient to multiply the height of the fall by the value in kilogrammes of the weight. This product would in fact represent the available work, but it is not entirely expended by the friction of the revolving plates, and thus transformed into heat. A part is employed to overcome the resistance of the string, and that of the air, and another part to produce a little heat by the friction of the pulley, and that of the axis which carries the plates. These different portions of heat are not appreciated by the thermometer. Then, when the weight touches the earth, there is a blow or shock which creates heat, and which cannot be measured. It would be possible to estimate the quantity of work thus expended by certain contrivances

which it would be tedious to describe; and by subtracting this sum from the whole available work produced by the descending weight, we should obtain the exact quantity to be compared with the heat measured by the thermometer. Such is the celebrated experiment made by Mr Joule about 1843.

6. *On some grand natural phenomena in which mechanical force is converted into Heat.*

Let us leave the laboratory, and take a few moments' rest from the fatigues of our long argument whilst contemplating the grand natural phenomena in which heat is engendered by causes similar to those we have just studied.

For instance, we are travelling in a railway train. Whenever the train is about to stop we hear the grinding of the break, which is pressed against the wheels for the purpose of checking the motion. The train represents an animated mass travelling at a great speed: by the friction of the break, this mass is brought to rest, and heat is created on the rubbing surfaces. The work which has been spent in giving to the train its speed, is equivalent to this heat. The train starts again: the piston being pressed by the steam transmits the effort to the driving wheels of the engine; these in their turn transmit it to the rails, and these react. It is this reaction of the rails which makes the train advance—a real exterior force pushing behind. If the friction ceased, and if the rail were perfectly horizontal, the train would behave like a body removed from the action of gravity, and which has received an impulsion. It would move uniformly by reason of its inertia, without a renewal of the impulsion or a fresh expenditure of motive work being necessary. But friction always takes place, both at the axle-tree and on the rail. This is the reason, in the hypothesis of a horizontal road, that it is necessary to keep the steam in action to maintain the force. The motive work which the machine expends is said to be employed in overcoming friction. In reality, it is employed to create the heat which accompanies the friction; and as this work is affected by the expenditure

of the heat disengaged by the combustible in the furnace of the machine, it may be said that the function of the steam is to absorb the heat from the fire, and that of the rubbing surfaces to make an equal quantity of heat reappear, which, of course, passes freely off. In this manner nothing is lost in nature, and the whole difficulty consists in following the transformation of forces. In the motion of a train over the horizontal road, the heat of the fire is continually being transformed into mechanical work, and the work itself is being continually reconverted into frictional heat; the motion of the atoms in combustion is transmitted to the larger masses of the train, and these masses in their turn transmit it to other atoms by the operation of friction.

We can now understand the importance of greasing the axles of wheels sufficiently. If the person charged with this duty neglects to renew the grease contained in the boxes attached to the end of the axles, the friction becomes more intense, the amount of heat created augments, and the stoker is obliged to burn more coal or carbon. There is, at the same time, a risk of fire and increased consumption of the combustible materials, both which should be avoided.

Let us visit the falls of the Rhine, the finest cataract in Europe. The waters of the stream fall from a height of 20 metres (about 66 feet), with an expanse of 100 metres (about 330 feet). Nature has placed this immense *obstacle* across the bed of the river, and gravitation makes every kilogramme of water which arrives on its crest to fall the height of 20 metres. There is, therefore, a work of 20 kilogrammetres converted into heat, exactly as in the case of the falling weight already discussed. The speed of our kilogramme of water increases in the fall; afterwards this increase is extinguished in the whirl and turmoil of the waters, for the current of the river is not more rapid on one side than on the other at some distance from the fall. It is in the midst of the boiling waves at the base of the cataract that the mechanical effect of gravitation is replaced by heat. A mass of water of 21 kilogrammes engenders in this fall one thermal unit. Admit that 210 cubic metres of water fall

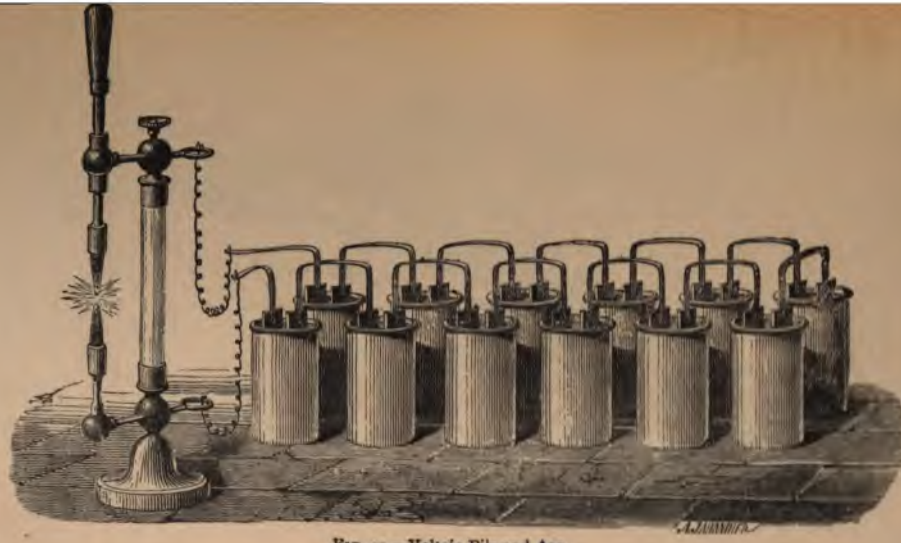

FIG. 21.—Voltaic Pile and Arc.

hydrogen forming in the tissues of the plant those substances sought by animals for food. We are led to believe

FIG. 22.—Spathe of the Arum.

that this decomposition spends heat, and that this heat comes from the sun.

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FIG. 22.—Spathe of the Arum.

that this decomposition spends heat, and that this heat comes from the sun.

polished metallic surface of this kind is called a **burning-mirror**, and the point at which the sun's heat is concentrated is the focus. The phenomenon exhibited by the mirror, and from which results the formation of a focus of heat, is termed the *reflection* of heat.

FIG. 23.—Burning Mirror.

A burning-mirror of large size is represented by fig. 23. Its frame carries three converging bars, which provide the focus with a support to carry the substances to be submitted to the reflected rays. Very large burning-mirrors have been made, and it is on record that they have displayed remarkable power. The Tschirnhausen mirror, constructed in

1687, was made of copper; it had a diameter of about 70 inches, and its focus was about 6 feet from the surface. It melted copper and silver, and vitrified brick. In 1757, Bernières constructed for Louis XV. a burning-mirror made of tinned glass, of much greater power. In this kind of mirror, a layer of tin-amalgam is deposited on the convex surface, and the rays which reach the concavity traverse the glass, and, being reflected back from the metallic surface, go forth again by traversing the glass a second time. There is certainly a small amount of reflection on the concave surface of the glass; but its effect is much feebler than that from the tinned surface. Among celebrated experiments, we may also mention that of Mariotte, who ignited gunpowder with a mirror constructed of ice; and, above all that, of Buffon, who succeeded in burning wood at a distance of 200 feet from the mirror. His apparatus was composed of a hundred flat mirrors of tinned glass, each a superficies of six inches square, and adjusted with hinges to a frame; so that the whole constituted a spherical surface. This experiment shows the possibility of the well-known legend of Archimedes. "That philosopher," says the historian Zonaras, "having received the sun's rays on the surface of a mirror, with the help of these rays, gathered together and reflected by the imperviousness and polish of the mirror, inflamed the air, and lit a great flame, which he threw entirely over all the vessels that were anchored within the sphere of its activity."* This incident is supposed to have occurred at the siege of Syracuse by the Romans, whose vessels were burnt with the help of burning-mirrors. We have just seen the possibility of lighting wood at a great distance by joining together a number of mirrors; but we can better understand the expression of the historian, by supposing that Archimedes used mirrors to set on fire combustible substances, which were afterwards thrown over the enemies' vessels.

We shall now proceed to show that the laws of the reflection of heat are the same as those of the reflection of light and sound.

Take two concave mirrors of polished copper, exactly

* Traité de Physique de Daguin.

alike. The reflecting surface is understood to be strictly spherical—that is to say, all its points are at an equal distance from a point called the centre of the curvature. An imaginary straight line passing through the centre and the middle of the surface is the axis of the mirror. To make the experiment we place our mirrors face to face (fig. 24), in such a manner that their two axes exactly coincide.

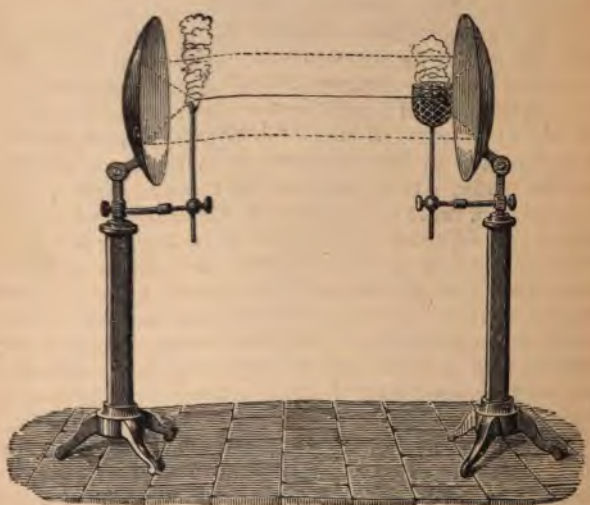

FIG. 24.—Two opposed Mirrors.

Now put some pieces of lighted charcoal in a grate of iron wire, and place this grate near one of the mirrors, in the line of the axis and at an equal distance from the mirror and from its centre of curvature. If we operate in the dark, we shall find, with the help of a small piece of paper, that a focus of light is produced before the second mirror at a point situated on its axis, at an equal distance from the mirror and from its centre. The explanation of this is as

follows:—A ray starting from the incandescent carbon meets the first mirror; it is reflected in a direction parallel to the axis, and necessarily strikes against the second mirror; it is reflected again thence, and passes by the focus. All the rays of light received by the first mirror travel similarly, and meet in the focus of the second; hence the concentration of light. If this reasoning is exact, we should be able to remove the mirrors to a greater distance apart, without changing the effect, and this indeed may be proved.

At the focus of light opposite the second mirror place some tinder or gunpowder, taking care to interpose between the mirrors a wooden screen to intercept the rays. Directly the screen is removed, the inflammable matter will take fire, and we shall have proved, in a striking manner, that the focus of heat coincides with that of light. In a word, that heat-rays travel in the same direction as light-rays.

Take away the charcoal, and put a watch in its place: we shall not hear the sound of its ticking in the neighbourhood of the second mirror at a spot taken by chance. But if we place our ear at the exact spot that our preceding experiments have determined to be the focus of the mirror, we shall hear it distinctly, although there may be a distance of several yards between the two mirrors. It is thus proved that the propagation of sound follows the same law as that of heat and light. What then is sound?

A sonorous body is animated by an oscillatory movement; its entire mass is in vibration, and each of its vibrations produces on the surrounding air a pulsation which is transmitted to our ears. The impression received by this organ is followed by the sensation which we perspicuously distinguish from other sensations by calling it sound. The direction in which a series of pulsations is transmitted through the air is called a sonorous ray. In any treatise devoted to the philosophy of sound will be found experimental proofs of this mode of transmission, which, moreover, is analogous to that of liquid waves. In our experiment, each sonorous ray reaches the ear after two reflections from our mirrors.

The rays of heat and light behave like the rays of sound.

Imagine, in place of the vibrations of the sonorous body, those of the ether contained in the source of such heat and light, and, in place of the pulsations propagated through the air, analogous pulsations propagated through the ether comprised between the two mirrors, and you will have a kind of picture of the radiation of heat and light.

2. *Refraction of Heat.—Burning-glasses.*

The heat that falls on any body whatever is not entirely reflected. Generally, a portion is absorbed; it is employed to warm the body, to raise its temperature, or even to melt it or to vaporize it. Another part traverses the body as light passes through the glass of our windows. The metals which we have used in the construction of mirrors completely absorb that part of the heat which is not reflected; they are not traversed by any ray, whether calorific or luminous. In other words, the metals are not transparent either to heat or light. For this reason they are employed as screens; it is the same with wood and with stone.

The study of the transmission of heat will conduct us to the fundamental laws of radiation, to those which explain the infinite variety of the phenomena of propagation. Already the study of reflection has taught us in what sense to accept the word ray, and how we can follow a ray in thought so as to explain the facts which we observe. It is sufficient to remark that we can feel the warmth of the sun's rays through a pane of glass for it to be understood that glass is transparent to the sun's heat. Imagine a piece of clear glass having the form of a lens, and presenting two spherical convex faces, (fig. 25.) Place it in the sun, we shall find, with a piece of paper, a point where the light is concentrated; this point is on the side of the lens from which the rays of light and heat escape; it is called the focus. This observation shows that a ray of light in traversing the lens deviates from its original direction; we say that it is refracted, and we call this change in direction *refraction.* Now, the heat is equally concentrated at the same point; because the paper takes fire there. If we place the bulb

of a thermometer in the focus, the mercury rises rapidly in the tube, a fact which shows the heating power to be very considerable; whilst, if the thermometer is not exactly at the focus, the mercury rises only a few degrees. Therefore the heat rays are also refracted, and they follow the same route as those of light: a new result which, like that afforded by reflection, proves the analogy between heat and light.

The property of burning-glasses was known long before the Christian era. It is indicated in the following dialogue

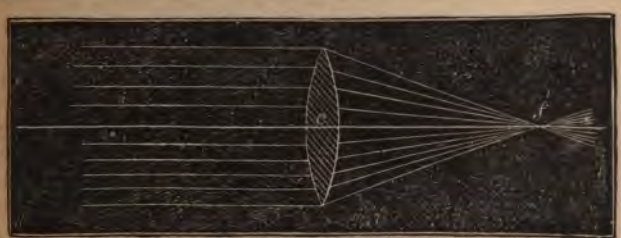

FIG. 25.—Converging Lens.

which occurs in the "Clouds" of Aristophanes:—"Have you seen at the druggists' shops the beautiful transparent stone which they use to produce fire?"—"Do you mean glass?"—"I do."—"Come, what would you say, pray, if I were to take this when the clerk was entering the suit, and were to stand at a distance, in the direction of the sun, thus, and burn up all the writings?"

The burning-glass of Tschirnhausen was about three feet in diameter, and it even melted gold. In 1763 experiments were made in England with a lens of ice, 10 feet in diameter, which was exposed to the sun, and in the focus of which gunpowder was ignited. Buffon constructed a liquid lens, by uniting by their edges two large plates of glass, having the shape of watch-glasses, so as to form a kind of lenticular trough, which was filled with liquid. The most powerful

form than that of the lens, we shall arrive at fresh results much more important in relation to the constitution of calorific rays. It is only by slow degrees that we arrive at

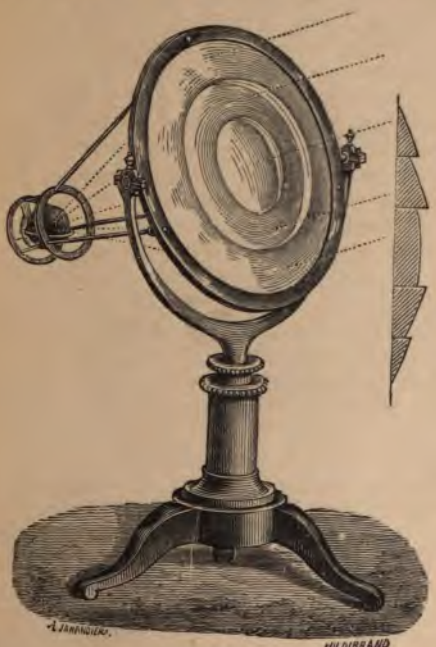

FIG. 26.—Lens.

truth. Each discovery we make is but a step in advance which prepares for further progress.

3. *Physical identity of a ray of light with a ray of Heat.—Luminous and calorific spectra.*

For a long time the analogy only of radiant light and heat was admitted: it is since the recent works of the Italian Melloni that we have been led to admit their

identity. It is now generally believed that the sources of heat and light send through the ether pulsations of only one kind, and that these pulsations may differ among themselves according to the rapidity of their succession; much as shrill sounds differ from deep sounds in the greater rapidity of the vibrations of the sonorous body. A ray which propagates in the ether a series of very rapid pulsations acts specially on our eye, and determines there a sensation of light, because the nerve of the eye is organized to that end; on the contrary, a ray which propagates a series of slow pulsations, makes no impression on the eye, whilst it affects the nerves of our skin, and causes there a sensation of heat. But there is no essential difference between these two rays so far as the motion which they represent; mechanically, they are of the same kind; they differ only in their quality relatively to our senses.

As the clear understanding of this conception is intimately connected with that of the propagation of sound, it may be useful to recall several experiments which have been made in the latter branch of study. First, let us suppose we are provided with a wheel made of copper, the circumference of which is cut into thirty-four equidistant teeth; this wheel being capable of turning on its axis (fig. 27). If we press the card on its edge, we shall distinctly hear the noise each time the card touches a tooth. But turn the wheel faster and still faster, the blows will then follow upon each other closer and closer, and will soon produce a continuous sound. The number of turns made by the wheel in a second may be counted; suppose it makes ten turns, there will then be 340 blows in a second, and as many pulsations communicated by the air to our ear. These pulsations succeed each other in the air at a distance of one metre, and at an interval of $\frac{1}{340}$th of a second; so that when the 340th leaves the card, the first will have reached bodies 340 metres distant. The sound that we shall hear is nearly that called *mi* in the lowest octave of the violin (mi_2).

Further, if the wheel be made to rotate ten times faster, we shall have 3,400 pulsations per second. The distance between two consecutive pulsations in a sonorous ray will

ne one decimetre; and when the 3,400th pulsation leaves the card, the first will have attained bodies placed at a distance of 340 metres, as before. The sound heard will be nearly *la* on the third octave above that marked by the preceding experiment (la_6).

The distance which separates two consecutive pulsations, or sonorous waves, is called in physics the length of the

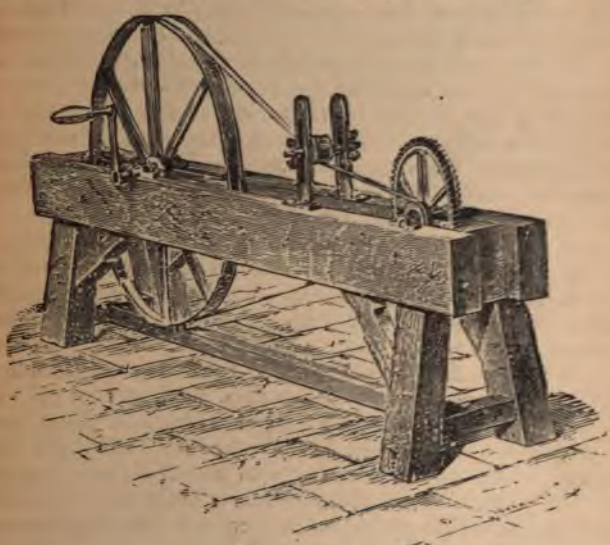

FIG. 27.—Savart's Wheel.

wave. The sharpest sounds, then, arise from the shortest waves; in the preceding examples we had two waves, one measuring one metre, the other a decimetre.

Now, fix on one and the same axis two wheels, having respectively 34 and 340 teeth (fig. 28,) and cause them to revolve ten times in a second. On touching the edges of these wheels alternately with the card, we shall produce, one after the other, the same sounds as before; and a person

gradually moving farther from the instrument will continue to hear them at the same interval of time; they will appear to him to succeed each other in exactly the same manner. Of this fact we may assure ourselves any day, when we hear in the distance a musical air: the sounds reach our ear in the same order and with the same pitch, at whatever distance we may be; the only difference is in the intensity: we do not, indeed, hear so well at a distance, but it is always the same air. The conclusion to be drawn from this is, that deep and sharp sounds travel with the same speed. With the apparatus we have just described, at a distance of 340 metres, two sonorous rays will reach our ears; in one of them, that giving the bass sound, there will be 340 waves, measuring one metre; in the other, that giving the sharp sound, there will be 3,400 waves, measuring one decimetre each. But in both cases alike a second of time will have elapsed between the departure of a wave and its reaching us. The distance travelled by any wave in a second is called the speed of the sound. It is 340 metres in the air; it would be different in water, in the earth, or in a gas different from the air.

This study of sound will enable us to distinguish between the different calorific or luminous rays. The source of the ray replaces the sonorous body; the ether is supposed instead of the air. There are in ether waves of different lengths, which can also travel with the same speed side by side without being disconcerted. Only the numbers which measure heat and light are very different from those which measure sound. In a ray of red light, for example, it has been found that there are 16,000 waves per centimetre; that its speed is 308,000 kilometres per second; and, as a consequence, that it makes, on entering the eye, more than 496 millions of millions of pulsations. The violet ray is estimated, in the same way, to make 699 millions of millions of pulsations.

These numbers are all the results of learned and painstaking researches of distinguished experimenters. We have quoted them to express precisely our thought, and to put the problem clearly before the reader; but our real busi-

ness at present is with the principal phenomena which have led to this theory. The following experiment shows that the rays emanating from the sun are separable into rays of

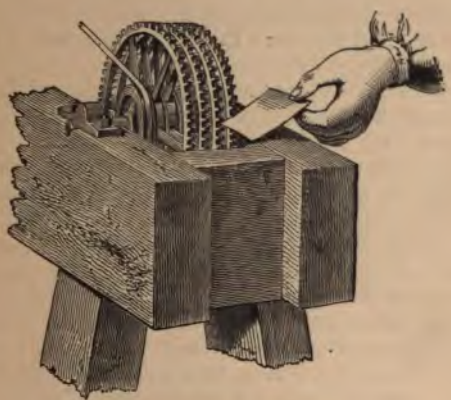

FIG. 28.—Savart's Wheels.

various qualities, in consequence of the inequality of the simultaneous waves which compose them.

A hole is made in the shutter of a dark room, a mirror being placed outside to reflect the solar rays into the room (fig. 29, *frontispiece.*) A piece of rock-salt, cut into the shape of a triangular prism, is placed in the direction of the rays in such a manner that they fall over only one angle of the prism. If this precaution be taken, no attention need be paid to the other angles ; that is to say, the piece of rock-salt may be of any shape we please, so that it is terminated by the two planes forming the angle. In traversing this angle the rays change their direction, deviating to the side of the room towards which the interior of the angle is turned. The refracted rays are received on a screen of white paper, producing the beautiful image seen in the coloured frontispiece.

A luminous band composed of seven magnificent colours is displayed on the screen in the following order:—

Violet, indigo, blue, green, yellow, orange, red.

The relative position of these colours shows that the deviation of the rays occurs in a decreasing ratio from violet to red.

Newton, who first made this beautiful experiment, has called this image the *solar spectrum.* It is usually described in optics as being effected with a glass prism. We have chosen rock-salt for this experiment because our object is to study the calorific rays, which, as well as the rays of light, pass freely through this substance. If we leave for a certain time a very delicate thermometer, such as a small thermo-electric pile, to the separate action of each of the seven colours of the spectrum successively, starting from the violet, the temperature will be observed to rise, but not equally. As we approach the red, the increase of heat is greater in proportion. Now pass the red, and continue to move the thermometer in the same downward direction, but in the dark part. We shall now see that the heat becomes much greater than before, and that it reaches a maximum at a point situated a little beyond the red, and then decreases, though it is still appreciable to a considerable distance. It appears that there are in the solar rays some which are purely calorific, which are less refracted by the prism than the luminous rays, and which are distinguished amongst each other by the amount of their deviation and by their intensity.

The luminous band, composed of seven colours, indicates to us that there are rays of light which are distinguished equally by their deviation and their manner of affecting our eyes. Those which are the most refracted produce the sensation of violet; then come six other rays, each producing a special sensation of colour. These luminous rays are also calorific.

To complete our observations, it is necessary to make the rays of each colour fall successively on a second prism similar to the first. This we can do by means of a screen

provided with an aperture, as shown in fig. 30 (*frontispiece*). We shall find in this case that the separated rays undergo no further modification. The violet rays are simply deviated by the second prism; they remain in the same state relatively to colour and heat, and it is the same with all the rest. The rays issuing from the first prism are called simple, and the rays coming from the sun are said to be composed of these simple rays: they separate in traversing the prism. The various simple rays are characterized by the deviation they undergo when falling in a similar manner on the same prism. Those which deviate the most are said to be most refrangible, or possessed of a greater refrangibility than the others. Instead of "deviated" we have, therefore, sometimes used the word "refracted." Thus the scale of refrangibility decreases from the violet to the red, and it decreases still more in the purely calorific rays. In fine, delicate experiments have shown, that if a simple luminous ray be submitted to a variety of operations which change its luminous intensity, it preserves a heating power which undergoes exactly the same changes. But there is not in consequence any reason to suppose that the luminous ray is continuously accompanied by a ray of heat distinct from itself. It is much simpler to admit that the same ray is capable of producing two effects, heat and light, and that there is no distinction save in relation to our senses. In this manner only can the observations be explained.

We have still to discover how the theory of waves explains the separation of simple rays, the mixture of which constitutes solar rays. It will be sufficient to ascertain what happens on the face of the prism by which the rays enter, because the face from which they issue produces the same effect. The separation has commenced at the first face, and is simply continued at the second.

Let us suppose two rays, the one violet, the other red, arriving together on the prism. The waves of the first are shorter than those of the second. In entering the prism they become still shorter, and they travel more slowly than in the air, because glass is a denser substance than air. It may be demonstrated mathematically that the diminution of

these waves occasions the deviation of the rays, and causes them to continue their course more nearly perpendicular to the face on which they entered. Further, the red waves being longer than the violet, travel faster on the substance of the glass, and from this again results that the red ray is less refracted than the violet ray. What we have said concerning these two rays is applicable to the others. Hence they separate in their order of refrangibility.

Our observation that the various waves of light do not travel with the same speed in one and the same transparent substance, may have appeared to the reader to be inconsistent with what we have before ascertained concerning the waves of sound. But it must be remembered that it is only in ethereal space that the equality of speed is true; in solid bodies the effect of the material molecules is to diminish the speed of the luminous or calorific rays in direct relation to the decrease in length. The analogy of sonorous with ethereal waves is complete.

It is in consequence of the united efforts of physicists and geometricians that we are able to examine these questions; and in pointing out their results we have simply wished to give an idea of the power which the human mind acquires when it is able to apply mathematical reasoning to the laws which have come under its observation in the study of natural phenomena. The mechanism of matter is discovered; the molecules, with their harmonious movements, appear to the natural philosopher just as the worlds of celestial space appear to the astronomer who knows how to penetrate the mystery of its infinite depths.

4. *Sifting of the rays.*

In our study of transmission we used, by preference, a prism of rock-salt. If we had used one of glass, we should have obtained a solar spectrum identically the same. But we should not have found the less refrangible heat-rays, which, being invisible, we call dark. The conclusion to [illegible] wn from this observation is, that the dark rays are

absorbed by the glass, the luminous rays alone being transmitted. Further, if we take a glass prism coloured red, for example, not only will the dark rays be arrested, but also a portion of the luminous rays. The spectrum is incomplete; the red part is seen very well, but both blue and violet are missing. In general, most of the colours, with the exception of the red, are pale; thus the red rays alone escape absorption, the others being partially or completely absorbed. Indeed, some varieties of red glass may be found which let no other rays pass except those of this colour. The red in such a glass is called simple, whilst the red in the preceding is compound.

It will now be easy to imagine the immense variety of effects produced by transmission through transparent bodies. We have simply to imagine, in place of the solar rays, a number of grains of all sizes, and, instead of transparent bodies, sieves having holes of all possible sizes; we shall obtain a rough idea of the diversity in composition that the transmitted part may present. One sieve has holes larger than the grains, and so all pass freely through. In this way rock-salt allows rays of all kinds to traverse it. Another sieve has smaller holes, the larger grains are kept back. In the same way glass retains the dark rays. Another sieve has still smaller holes; grains which passed before are now stopped: this illustrates the coloured glass, which retains the dark rays and all other luminous rays but the red.

Under the last-named sieve place another similar one. It will give passage to all the grains which have traversed the first without retaining anything. To this we may compare the transmission of solar rays through two transparent plates of the same kind. The heat which falls on the second after issuing from the first passes freely, because it has been sifted, to make use of the original expression of Mr Tyndall. For example, solar rays fall on to a pane of glass; the luminous rays are alone transmitted: they fall again on a second pane of glass, and are no more arrested; so that the glass in the second case appears not to absorb heat, and in the first to absorb a great portion: this happens because the rays which reach the two glasses are not of the

same kind. It follows that transmission depends both on the substance which forms the medium, and on the nature of the rays themselves.

Again, let the two sieves, placed one above the other, be different; the first having large holes, the second having holes smaller than the grains. That which is passed through the first will be completely stopped by the second. Here is an illustration of solar rays, meeting first a red-glass medium, and then a blue one. The first glass has allowed the red rays only to pass, the second retains them; so that in placing the two glasses one above the other, an opaque body will have been formed of two transparent bodies.

Thus the transmission of rays is analogous to a process of sifting, but only when results are compared. The mechanism of the transmission is not in question, but it must not be supposed that a ray traverses a plate in the same way that a grain traverses a sieve. After having made the experiment with the solar spectrum, and having seen the prism separate the single rays which compose solar rays, it might naturally be asked, why our windows do not effect this separation? why light entering white passes out white?

The answer to this question is simply as follows:—The surfaces of entrance and of issue in window-glass are parallel planes, whilst in the prism they form a certain angle. It is this which causes the difference in the two modes of transmission. In fact, if we unite two similar glass prisms so as to form a plate with parallel surfaces like a pane of glass (as fig. 31), we shall find that the solar rays will traverse it without being decomposed. This happens because the rays, after diverging from the first prism, are refracted in a contrary direction by the second. Thus they collect together again, and re-form on issuing rays similar to and parallel with those which arrived from the sun.

Although separation does not take place, the absorption is the same as with the single prism, with this difference, that the absorbable rays are completely arrested by a sufficiently thick plate with parallel faces; whilst in a prism, the absorption is never complete near the summit of the angle, in consequence of its small thickness. For this

reason, experiments in transmission and absorption are always made with *plates*.

To recapitulate: Solar rays are composed of an infinity of simple rays, which are distinguished amongst each other by their refrangibility, if we wish simply to express the facts, or by the length of the wave, if we wish to employ the lan-

FIG. 31.—Inverted Prisms.

guage of the dynamic theory. When these rays strike against any given body, some part of them is reflected, another part may be transmitted; the remainder are absorbed, and these absorbed rays warm the body in which they are retained.

5. *Influence of temperature on the emission of Heat.*

We learn to distinguish between the quantity of rays emitted by a given source of heat, and their quality. We shall first take into consideration their quantity. The more the temperature of the source is raised, the greater is the quantity of heat emitted; always supposing that the body towards which radiation takes place, maintains a temperature constantly inferior to that of the source. If, on the contrary, the temperature of this body, still remaining inferior to that of the source which does not vary, rises gradually,

the quantity of heat emitted by the source towards the body diminishes; until the temperature of both having become equal, it ceases altogether. The action is reversed when the body is hotter than the source; that is to say, the body now emits the heat; it becomes a true source of heat itself. In this manner the sun sends us heat because its temperature is much above that of our globe; but if the earth could acquire a temperature above that of the sun, it would in its turn emit heat towards the sun. The emission of heat by a body is therefore determined by the presence of a body having a lower temperature. For example: it is known that celestial space has a temperature of almost 200° C. below zero; the earth is therefore a source of heat relatively to space, towards which it incessantly radiates heat. A cloud comes in a given direction, the temperature of which is very far from being so low as that of space; consequently, the earth will send a less number of rays in this direction than if the cloud did not exist.

These principles will explain certain phenomena in which cold seems to be reflected like heat. These phenomena would lead a careless observer to imagine the existence of rays of cold distinct from rays of heat. No doubt a great error, as the following experiment will make evident.

Take two metallic mirrors, arranged as fig. 24, and, instead of pieces of charcoal, place a few bits of ice in the grate at one of the foci. At the other focus expose the bulb of a very delicate thermometer. The mercury will now be observed to fall, whilst, if we cover the mirrors, there is no appreciable effect. The explanation is that the thermometer plays the part of a source of heat towards the ice. The rays which it sends towards the latter are, not only those which travel directly, and which are insensible in amount because of the distance, but those also which fall on the mirror next to the thermometer, and which, being reflected towards the opposite mirror, act by reflection from it on the ice. As there is nothing in the thermometer to repair the loss of its heat, its temperature decreases. It is true that bodies placed in the room around the apparatus, becoming then hotter than the thermometer, radiate towards

it, and tend to repair this loss; but it is only when its temperature is sufficiently low that the process of compensation can be established between the heat lost and the heat gained by the thermometer; it then remains stationary, its temperature being a little higher than that of the ice, because a portion of its surface is submitted to the radiation from the room, which is supposed to be at a temperature above zero.

6. *Influence of the nature of the source on emission.—Correlation between emission and absorption.*

We have still to consider the quality of the rays emitted by a source of heat. First, there are *dark* sources, such as a piece of metal heated to 400° C., or a vessel of boiling water; such sources emit dark rays, which traverse rock-salt, but which are arrested by glass. Further, there are luminous sources which emit dark rays mixed with luminous rays; the last are transmitted by glass, while the first are arrested. The composition of the rays emitted, therefore, depends on the nature of the source of heat, and the properties of these rays change with it. Above all, the superficial covering of a body acting as a source of heat modifies their emission. Take a copper cube full of water, and make the water boil by means of a spirit lamp (fig. 32): the four vertical faces of the cube are at the temperature of the boiling water; but they differ in the state of their exterior surfaces. The first is blackened, the second is whitened, the third is of unpolished copper, and the fourth is polished copper. Apply to each of the faces of the cube in succession the bulb of the thermometer, taking care to intercept the radiation of the lamp towards the thermometer by a

FIG. 32.—Leslie's Cube.

screen. It will be found that the thermometer will be unequally heated by the several faces, and if we follow the above order we shall find the temperature to diminish. The blackened side allows the greatest emission of the heat rays; the polished one, on the contrary, renders the emission very feeble. The effect exerted by the state of the surface on the amount of emission may be proved without physical apparatus, by the comparison of a stove of cast-iron having a rough surface with a stove of polished iron. The first warms neighbouring bodies more than the second. Again, put similar weights of boiling water into two copper vessels, one of which is polished and the other blackened: you will find the first to cool more slowly than the second, and you will conclude from this that the emission from a black surface is greater than from a polished one.

FIG. 33. Voltaic Arc.

Inversely, if you put the same vessels full of cold water before the fire, the blackened one will get hot faster than the other. You will conclude from this that the absorption of heat by the first is greater than that by the second, so that you are led to think that the most absorbant bodies are also those which most easily emit heat. This correlation between emission and absorption is in fact established by numerous experiments, and it applies not only to the quantity of heat, but also to its quality. Thus a substance emits just such a group of rays, characterised by their refrangibility, as it has the faculty of absorbing. We ought to find, according to our theory of the identity of heat and light, that the same law rules the absorption and the emission of light; and this, in fact, has been proved in experiments made of late years on the solar spectrum. The following is an example: Put a piece of sodium in the bright light produced by the electricity of a Voltaic pile between two points of carbon, which light is called the Voltaic arc (fig. 33).

The vapour of the sodium will become a source of light, and it will emit in abundance certain yellow rays of quite a peculiar intensity. If we cause these rays of light to traverse a prism, we obtain a spectrum which presents a characteristic yellow band. Instead of putting sodium in the Voltaic arc, reduce it into vapour at some distance, so that the rays of which you are about to form the spectrum shall traverse this vapour; the spectrum will take the appearance represented in fig. 34 (*frontispiece*). The yellow rays are absorbed by the vapour, their place being occupied in the spectrum by a black band, indicating the absence of these rays. Such is the fundamental experiment which has led physicists to contrive a method of observation with the help of which we may discover, according to the spectrum of a flame, either the nature of the vapours existing in it, or the nature of substances traversed by the rays emitted by the flame before forming a spectrum. It is by this method that MM. Kirchhoff and Bunsen have found that the atmosphere of the sun contains iron, magnesium, sodium, calcium, and some other metals.

7. *Influence of distance on radiant Heat.*

In our study of heat emitted from any source towards a given body, it is necessary to take the distance between them into account. If the body be gradually removed from the radiant source to double or treble the distance and so on successively, the heat received by it will be four times, nine times, and so on progressively, smaller. The explanation is the same as that given in the case of sound, the intensity of which follows the same law. The body receives a certain number of pulsations on the part of its surface which is turned towards the radiant source. Imagine a hollow sphere, at the centre of which we have a source of heat, and the surface of which would pass through the body to which the heat radiates. We may, for simplicity, suppose that the latter is in the form of a disk, resting on the surface of the sphere, and that the entire sphere has a superficies a thousand times greater than that part of the disk turned

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towards the source. In this case the sphere will receive a thousand times more rays than the body.

Now suppose a sphere of twice the radius, with the body which we have assumed to be a disk placed upon it. The surface of this new sphere will be four thousand times greater than that of the body; but the same number of rays will arrive in the same time on the large sphere as on the smaller one. The large sphere will receive four thousand times more rays than the disk; therefore the latter will receive four times less than before.

8. *Various applications of the preceding principles.—Dew.—Atmospheric water vapour.*

The laws of radiation explain a great number of facts open to common observation. For example: our bodies are submitted to the warming action of the sun by day, and during the night to the cooling action of the celestial space. Were the transition from a state of excessive heat to one of intense cold too sudden, it would be dangerous to health. To avert this danger, nature has given to the negro, for example, who lives under a tropical sun, so black a skin, that the abundant emission of his own heat has the effect of cooling him. On the other hand, as the absorption of the solar rays might be too great and neutralize the beneficent action of this emission, an oily perspiration lubricates his skin, so that the rays may be strongly reflected from its surface. In other places, man's intelligence enables him to find the resources necessary for his protection. The Arab, who requires protection from the sun when crossing the desert, and far from any shelter, envelopes himself in white wool. This stuff absorbs the solar rays less than any other; it reflects them in every direction, and diffuses them. Among ourselves, the use of white cotton preserves the heat of our bodies, because it is reflected interiorly by the parts of the cotton, which are only separated from the skin by a bed of air. Black clothing is as a rule hurtful, because in the sun it absorbs its heat strongly, and in the shade it emits on the contrary that of our bodies; thus it rather aggravates

the effects resulting from sudden changes of temperature than ameliorates them. White clothing is more suitable, on account of its comparatively feeble powers of absorption and emission.

It is for the purpose of retarding the emission of their heat that nature has given to the animals living in polar regions a white coat; and in other regions where the winter is rigorous, the coat is only white during the duration of that season.

Opportunities for applying these very simple rules often occur. To preserve a body from the radiation of heat, give it a polished metallic surface if possible. Professor Tyndall mentions a very curious instance of this method of preservation. A plank of wood, upon which had been written characters in gold, had been submitted to the radiation of a large fire; the wood was carbonized all around the letters, but it was intact beneath them. The rays of heat had in fact been absorbed by the naked wood, and reflected by the gilding.

On the contrary, to augment the absorption of radiant heat, give to the body a black surface. It is for this reason that gardeners paint the walls for espaliers black, so that the solar rays may be absorbed, and the heated walls may afterwards radiate towards the fruit; the latter then receive both this heat and that which reaches them directly from the sun.

We frequently utilize the property possessed by glass of absorbing the dark rays and allowing the luminous rays to pass. In foundries, the workmen observe the flow of the metal through screens of glass. The luminous rays alone reach their eyes, and these are the less ardent. Above all, the eyelids must be thus preserved; the eye itself is less exposed, because its fluids stop the dark rays, and prevent the optic nerve from being burnt. In our gardens, the bell-glass we use to cover a young plant, acts by economizing the heat received from the sun. The luminous rays which have passed through the glass are absorbed by the earth and the plant; these emit dark rays only, which cannot escape through the glass. The air confined over the plant may thus attain a temperature above that of the exterior air.

The case is the same with our greenhouses, the solar rays having to traverse all the glass exposed to the sun.

If we want to contemplate examples of greater magnitude, we have only to cast a *coup d'œil* over our globe, considering it as a radiating, or, inversely, as an absorbing body.

In the night, terrestrial bodies gradually lose the heat they have received from the sun during the day. If the sky is cloudy, the rays emitted from the surface of the earth are absorbed by the clouds, which are colder; and this emission is smaller in the degree that the temperature of the clouds is higher. If the sky is clear, the emission of terrestrial heat is much more intense; because the temperature of the celestial space is excessively low; but it is not the same in amount with all bodies. Water emits more heat than the earth, naked, or clad with verdure. Among various bodies exposed on the surface of the ground, some radiate more heat than others, according to their nature and situation in reference to the sun and air. Those, for instance, from which a part of the sky is hidden by walls, trees, elevations of the earth, or any other shelter, emit less than if they were not thus sheltered. With the same amount of exposure, the radiation of metals is inferior to that of stones, and these again to that of the green parts of vegetables. Evidently, the greater the amount of radiation of a body, the greater its decrease in temperature. We see then that the cooling of terrestrial bodies during the night is very unequal.

The atmosphere is formed principally of air, a mixture of oxygen, of nitrogen, and of water in the state of transparent invisible gas; the latter must not be confounded with fogs, which are composed of liquid water condensed into the form of small visible drops. The atmosphere absorbs but little dark heat, consequently its emission is very feeble; hence it preserves, above a certain height, a temperature superior to that of the ground. Near the surface of the earth it becomes cool by reason of its contact with terrestrial substances, and its water vapour condenses on the surface of these bodies when their temperature is sufficiently low. The deposit of dew is unequal in different bodies. A piece of iron placed upon a stone in a meadow will

remain dry whilst the stone will be slightly wet, and the grass will be covered with dew. The temperature in the daytime being less in the spring than in the summer, the nocturnal cooling of certain terrestrial substances, such as the green shoots of plants, may descend below the freezing point; the water they contain solidifies, breaking the tissues, and the plants freeze. This phenomenon is called a white frost. In these cases the dew is no longer deposited in the form of liquid drops, but in that of *needles* of ice, which form the hoar-frost.

In Bengal, where the diurnal temperature is very elevated, ice may nevertheless be obtained by nocturnal radiation, some such artifice as the following being adopted as means: Rather shallow pits are filled with straw, which is a bad conductor of heat, and on this straw are placed flat open vessels containing water freed from air by being boiled. The water emits its heat freely, the straw preserves it from the heat of the soil, and ice is formed. It has been noticed that the most favourable nights for the production of ice are those during which there is but little dew, the sky being moreover clear and without clouds. Evidently, if there is but little dew, the atmosphere is only slightly humid. Thus the absence of vapour of water in the air is favourable to nocturnal radiation. It has been known, indeed, since the researches of Professor Tyndall, that water vapour absorbs 72 times more heat than the dry air with which it is mixed. The rays emitted by the earth traverse, therefore, dry air more freely than humid air, and nocturnal cooling augments with the dryness of the air.

The white frosts of the spring are fatal to agriculturists; and, ignorant of the true cause of this phenomenon, they have often accused the stars of exercising an influence on the earth which it is impossible they should have. As white frosts happen when the air is very clear and very dry, the moon shines in the sky with great brilliancy, and naturally attracts our attention; but there is no more reason to attribute a cooling action to her than a putrefying one, which has been also done, because it has been noticed that animal substances putrefy more rapidly under the same circum-

stances: it has not been noticed that these substances become abundantly covered with dew, and that it is the water which causes the putrefaction. Far from cooling the earth, the moon warms it by reflecting the rays of heat from the sun, as Melloni discovered with the help of very delicate instruments.

Now that white frost is explained by radiation, it is easy to understand the reason for having recourse to such means of protection as the thin matting with which gardeners cover delicate plants; also, the practice of protecting vines with clouds of smoke caused by lighting fires with resinous substances at that advanced hour of the night when the temperature approaches zero. This practice, which ought to be generally adopted in France, has been long known in several other countries, particularly in Peru.

The bodies which cool most during the night are also heated most in the day, as soon as the solar rays reach them. Vegetables appear to be an exception, but it must be remembered that the water they contain evaporates, and that evaporation consumes heat, which cannot then serve to raise their temperature. Dry earth exposed to the sun may acquire from 20° to 40° C. of heat more than the air, and black substances take an excess of temperature still greater. These facts illustrate the correlation which exists between the emission and absorption of heat. In winter time the solar rays determine the partial fusion of the snow which covers the earth; this fusion prevents the temperature of the soil from rising, and gives to it a humidity highly favourable to vegetation. The fusion is very slow, in consequence of the feeble absorption of the rays. To convince one's self of this it is sufficient to throw a little charcoal dust on the snow; the fusion becomes rapid around each grain of charcoal, because it absorbs much heat, and the track of the dust is soon drawn on the snow by a deep furrow. The snow absorbs dark rays better than luminous rays, and for this reason it melts faster under the trees; for when trees have been heated by the solar rays, they radiate in their turn the dark heat towards the snow which lies beneath their shadow.

The preservative character of snow appears again at night, when the sky is clear. The white carpet which covers our fields radiates feebly towards the celestial spaces; its temperature falls to a little below zero (32° Fahrenheit), and it prevents the plants buried in the ground from being too severely cooled.

We shall often again be called upon to admire the part played by water on the surface of the earth. Here we can only consider its relations to radiant heat, and we shall conclude this chapter with some observations on atmospheric water-vapour, feeling certain that it will throw a new light on the physics of the globe.

According to the experiments of Professor Tyndall, the water-vapour that a certain volume of air may contain absorbs about 72 times more heat than that air absorbs when dry. This applies equally to the quantities of heat emitted under similar circumstances.

At the bottom of a valley, with a river course, the air is necessarily more humid than on an elevated plateau or mountain. In the night, after a fine summer's day, when the sun disappears behind the hills, the valley is plunged in obscurity and deprived of solar rays before the surrounding heights. The humid air which it contains immediately begins radiating towards the celestial space, and the water-vapour, above all, renders this action very intense. The rapid radiation, in its turn, is the cause of a sudden cooling, owing to which the vapours condense in small imperceptible drops, which fall like a fine rain, though the sky is free of cloud. This is the evening damp.

As we rise in mountainous countries, we meet with strata of drier air, and they absorb less of the solar rays. The traveller who crosses during sunshine the glaciers of the Alps experiences the effects of the feeble absorption. With his feet on the ice, he feels throughout his whole body an insupportable heat. The solar rays freely traversing the dry air are absorbed by his garments, which become oppressively hot. The air is cold, nevertheless, because there is not enough vapour in it to retain the heat; and when a traveller passes from sunshine into shade, its excessive cold is felt.

It may now be easily understood why burning mirrors and glasses are so much more powerful on the mountains or, more generally, in a dry atmosphere.

The dryness of the air is, therefore, favourable to the heating of terrestrial substances during the day, and to their cooling during the night. Also, the driest countries suffer the greatest variations in climate. In the Sahara, the sand is burning, the atmosphere is like fire during the day, and the cold at night is excessive; ice even is formed. We find in the account of a journey recently made in Asia and in Oceania, by the Count Henry Russel-Killough, many curious details about the excessive temperature of Siberia, of Thibet, and of Australia, countries where the aridity is excessive at certain seasons of the year.

One day at Kaïnsk, in Siberia, the temperature fell, in four hours, from zero to fifteen degrees below it;* some days afterwards the mercury of the thermometer sank completely into the bulb, which seemed half empty, yet the tube itself marked thirty-five degrees below zero.† It will not surprise any to hear that, on the same day, brandy was frozen beneath hay and fur. "All this," says the author, "happened under the most dazzling sun. Clouds are impossible at a temperature when vapour is turned into stone, and the blood freezes in one's veins."

In Australia, there is sometimes a difference of 90° F. between the highest and lowest points of temperature marked by the thermometer. Our traveller has observed 120° F. in the shade, and 147° in the sun. "The mortality," says he, "especially of children, became alarming; birds fell from the trees as if thunderstruck, whilst others allowed themselves to be taken by the hand or came to quench their thirst in the interiors of the houses. Plants were burnt to the point of falling when touched, like the ash of a cigar." Captain Sturt has observed in Central Australia 129° F. in the shade and 160° in the sun.

* From 32° to 5° Fahrenheit. † Equal to 31° Fahrenheit.

CHAPTER V.

CONDUCTION OF HEAT.

1. *Bodies which are good conductors.*

WHEN we submit a part only of a body to the action of a source of heat, this part heats progressively the remainder of the body. This propagation of heat from one part to another in the interior of a body is called conduction. It proceeds very slowly, in which respect it differs much from radiation.

Conduction is easily explained by regarding each molecule of the interior of the body as submitted to the heating action of molecules hotter than itself, and to the cooling action of colder molecules. The molecule is in equilibrium when these two contrary actions, which follow the laws of radiation, exactly counterbalance each other. The molecules placed on the surface of the body are, moreover, submitted to the action of exterior substances; and here we must distinguish between two different actions, the radiation between the surface and distant objects, and the passage of heat from the surface to substances which touch it, or reciprocally, according as the substance is hotter or colder than these objects. This passage is a phenomenon of conduction, because it is effected from molecule to molecule; it differs from interior conduction, inasmuch as the molecules put into play are of different natures; it is distinguished by the name "exterior conduction." When a body is warmed by a source of heat in one of its parts, radiation and conduction determine a cooling action, and each part of the body

acquires a stationary temperature when this action exactly compensates the heating action of the source.

We proceed to describe a very simple experiment, showing the conductibility of solid bodies. Two bars of the same size, but different material, are placed as in fig. 35, the wooden balls being fastened to them by means of wax. At the point where the two bars join a spirit lamp is kindled, and the wooden balls will be seen to fall one after the other, starting from the point heated. Now, when a ball falls, it

FIG. 35.—Conductibility of solid bodies.

is because the wax which held it is melted, and this again is because the fusing point of the wax has been attained by the adjoining part of the bar. If one of the bars is iron and the other copper, it will be seen that a greater number of balls fall from the copper than from the iron; therefore, heat propagates farther in the copper. Hence, copper is called a better conductor than iron.

The conducting powers of a number of substances may be compared by adjusting equal bars of these substances to the vertical side of a metallic trough (fig. 36.) All the bars being covered with wax, the trough is filled with boiling water, and the wax melts to a greater or less distance from the trough, according to the conductibility of each individual bar. By such observations it has been easy to arrange a variety of bodies in a decreasing scale of conductibility as follows :—

SILVER.	BRASS.	LEAD.
COPPER.	TIN.	PLATINUM.
GOLD.	IRON.	BISMUTH.

A very trifling observation of daily occurrence is sufficient to remind us of the comparatively great conducting power of silver. Plunge in the same vessel of boiling water a silver spoon and a pewter or iron one. It will be found that the handle of the first will get hotter than that of the other.

FIG. 36.—Ingenhous's Apparatus.

In experiments on conduction, care must be taken not to confound the intensity of the heating with its rapidity. Conduction alone determines the first, whilst the second is a complex effect of conduction and another property possessed by bodies of which we shall treat in another section. Thus bismuth is a worse conductor than iron, and yet, with the above apparatus (fig. 36), we should see the wax melt quicker on the bismuth than on the iron. It nevertheless conducts less, because the wax which covers it melts to a less distance; thus the quantity of heat conducted is less. The same remark applies to our first experiment. It is the distance from the heated extremity at which the last ball that drops was fixed that must be noted, and not the rapidity of the successive falls.

Here is another experiment which at first sight may appear paradoxical, and which reproduces the same phenomena under another form. Place on the lid of a vessel full of boiling water two small solid cylinders, one of which is of bismuth, and the other of iron. It is understood that these cylinders are each of the same dimensions as the other, and that their upper extremities are covered with

wax (fig. 37). The heat from the vessel will gradually extend through the cylinders, and will at last melt the wax. The fusion commences on the bismuth because it conducts more *quickly*, not because it conducts *more* heat. We shall see by and by that, to raise equal weights of these two substances through the same number of degrees, we require four times more heat for the iron than for the bismuth. In order, therefore, that the temperature at which the wax melts

FIG. 37.—Conductibility of Iron and Bismuth.

may be attained at the upper extremities of the cylinders, it is obviously necessary that the iron should have transmitted more heat than the bismuth. Suppose the quantity of metal in each case is one gramme; then we say the gramme of iron will have received four times more heat than the gramme of bismuth before fusion commences, and for this very reason it has taken longer to get hot.

Substances which are good conductors of heat, such as the various metals, feel cold to the touch. It is because the hand that touches them, having a higher temperature, owing to the natural heat of the blood, gives up heat to them by virtue of conduction; and this heat being rapidly diffused throughout their mass, the loss of heat which the hand

suffers is continually repeated, and becomes very sensible. But, on the other hand, those metals are not always the *best* conductors which appear *coldest* to the touch. The effect depends on the rapidity of the transmission, as well as on the conductibility: and the one phenomenon is as complex as the other. Nevertheless, the great differences in conductibility may be recognised by the simple contact of the hand. Thus, wood appears less cold than marble, and marble less so than metal. The order in which we have named these three substances is that of their relatively increasing conductibility. It is supposed that the three bodies are touched after attaining the same temperature by remaining for some time together in the same room.

FIG. 38. Double Cylinder of copper and wood.

The same reasoning applies also to the following experiment. Round a cylinder constructed one half of copper, the other half of wood, roll a sheet of paper (fig. 38), and plunge the white surface into a flame for some moments. The fact of the cylinder being composed of two different substances will soon make itself apparent. That part of the paper which covers the wood is seen carbonized; that which covers the copper remains white. This takes place because the copper, a good conductor, takes the heat from the paper as fast as it comes from the flame, whilst the wood allows it to accumulate.

We also find a very curious example of conductibility in a property of metallic gauze, which has given rise to one of the most beneficent applications of scientific knowledge in practical life. If we place a piece of wire gauze over the flame of a jet of gas (fig. 39), the flame does not traverse the gauze; the exterior stratum, or hottest part of the flame (as shown in Chapter III.), reddens the gauze, and the circle of fire thus traced is a new demonstration of the constitution of flame. No combustion takes place above the gauze, which, however, gives free passage to the combustible gas. This may be proved by presenting a lighted match above the gauze, when we shall see the gas burn;

or we may extinguish the gas at the jet, and replacing the gauze, we can light it above without the flame passing below. The metallic gauze, therefore, intercepts the heat

FIG. 39.—Properties of Metallic Gauze.

only; it sufficiently cools the ignited gas to prevent the combustion commenced at one side from taking place at the other. This cooling is due to the conductibility of the copper wires which compose the gauze, exactly as in the preceding experiment.

By taking advantage of this property of metallic gauze Sir Humphry Davy constructed the safety-lamp for the purpose of protecting coal-miners from the terrible accidents to which they are exposed by the disengagement of fire-damp. Each blow of the pickaxe which disengages a block of coal liberates a certain quantity of this substance, a gas formed of carbon and hydrogen, which exists naturally in the interstices of the coal. As the mine is always at a considerable depth in the earth, it is worked by digging galleries, and consequently the fire-damp (as miners call this gas) remains in them, mixed with a proportion of atmospheric air. If a light approaches this mixture, explosion takes place, in consequence of the rapid combination of the carbon and hydrogen with the oxygen of the air. The poor miners may be burned by the flame, or killed by the shock of the explosion; and even if any of them escape these two causes of death, they are often asphyxiated by the carbonic acid gas which fills the galleries after the

combustion. It is therefore necessary, above all, to ventilate the mines properly, to make considerable volumes of air circulate in the galleries, so as to carry the fire damp away as fast as it is disengaged; and lastly, to give the workmen a means of being warned of its presence as soon as there is any danger.

To illustrate this, surround the flame of an oil-lamp (fig. 40) with a covering of metallic gauze, and we shall see what happens when this lamp burns in the midst of the fire-damp. The combustible gas will enter the lamp through the meshes of the gauze, and will burn there by contact with the flame of the oil; which will therefore become elongated and pale, and will entirely fill the interior of the network. But this flame will not be able to pass out, if the meshes of the gauze are sufficiently close, and if there are no holes formed by rough usage. The miner being warned by the appearance of the flame in his lamp, should, of course, hasten to quit the gallery, but yet do so cautiously, without shaking the lamp, because it is still possible that little incandescent particles may escape through the gauze before it has had time to cool them. In this case the interior flame will extend outwards mechanically, and explosion will take place.

FIG. 40.
Sir Humphry Davy's Safety Lamp.

It is plain from this that scientifically, and indeed for all practical purposes, the problem how to secure safety to our miners has been satisfactorily solved. Unhappily, the employment of Davy's lamp necessitates on the part of the men certain precautions, and these involve a certain amount of intelligence. When kept in bad repair it becomes a

source of danger. Some of the wires may be already partly destroyed by oxidation; the flame, enlarged by the fire-damp, then completes their destruction; the rotten gauze yields to the pressure, and explosion takes place. Thus accidents cannot always be avoided. These considerations have led to the invention of the electric lamp, burning in a vacuum tube, by which Davy's lamp may now be advantageously replaced. To describe it in this book would, however, be to depart from our proper task.

2. *Substances which are bad conductors.*

As yet we have occupied ourselves chiefly with solid bodies, which are good conductors of heat. Stones, glass, wood, and animal and vegetable tissues are bad conductors, through which heat is transmitted with difficulty. These substances will even completely arrest heat when in the state of powder or fibre, which is due partly to the fact that mechanical division destroys molecular continuity, which is necessary to conductibility, and partly that it interposes between the particles of the solid body layers of air, which conduct heat very badly. Thus, we can hold a red-hot cannon-ball with impunity, by covering the palm of the hand with asbestos. Artillerymen transport red-hot cannon-balls in wooden wheelbarrows filled with sand. Similarly, ice is preserved in sawdust; in the United States, ships are loaded with it in blocks of about two hundredweight, which are surrounded with sawdust, and thus sent into warm climates. In 1851 the export of ice amounted to 50,000 tons, and the cost of sawdust for its transport amounted to nearly £3000. In spite of this precaution, a part of the ice melts during the voyage. In the passage from Boston to Calcutta four-fifths are melted in consequence of the long passage and great heat.

In the construction of ice-houses the feeble conductibility of bricks is utilized. An ice-house is a deep pit lined with bricks (fig. 41), to prevent the heat of the soil from reaching the ice which is stored in them. The roof is covered over with straw, to intercept the heat of the sun, and trees are planted around, the foliage of which serves

as an additional screen. Air must also be prevented from circulating in the interstices of the ice, to effect which the pit is filled up with water during the winter, so that by freezing it unites the pieces of ice into one solid mass. On

FIG. 41.—Ice-house.

the approach of warm weather, the ice gradually melts to some extent, and the water thus formed drains into a well, through a grating provided for the purpose, at the bottom of the pit.

On account of their slight conductibility, bricks are used in northern countries for the construction of stoves. Advantage is taken of their property of cooling slowly, after having been strongly heated. The fire is lighted only in the morning, and when all the fuel is transformed into hot coals, the openings are closed; the heat is feebly radiated

by the exterior surface of the stove, which is covered with glazed delf, and it is sufficient to compensate the loss of heat by the walls of the room. Brick walls are also preferable to those constructed of stone, which should be thicker, because the latter substance conducts heat better than brick. An excellent wall would consist of two wooden partitions filled with sawdust. It must be remarked that the same walls are good for hot countries as for cold; because by taking care to keep all openings closed during the day, they prevent the outer heat from entering.

As an example of the singular facts explained by conductibility, Professor Tyndall mentions an instance of a steam-vessel being nearly lost under the circumstances mentioned below. It happened, during a sea-voyage, that the engine-boiler became covered interiorly with a deep layer of earthy matters, deposited by the water. Deposits of this kind always occur on the sides of vessels in which ordinary water is boiled, the material being dissolved by the water from the earthy beds it has filtered through. In the above instance, however, the deposit had been allowed to collect beyond measure. Now this crust is a very bad conductor of heat; the heat of the furnace therefore traversed it with difficulty; so that, to obtain sufficient steam to work the engine, it was necessary to burn more fuel than customary. The supply was exhausted before the ship had arrived in port; they had then to burn the deck and all the wood that could be found in the vessel. The cause of this unprecedented consumption of fuel was discovered after arriving in port.

Tissues of organic origin are the worst conductors of heat. Many animals and vegetables are able to resist sudden changes of temperature, owing to the perfection of their natural clothing. We ourselves try to imitate nature in our apparel. Woollen stuffs prevent the body from losing its heat in winter, and from absorbing that of exterior bodies in summer, for which purposes it is more suitable than cotton, because it is a worse conductor than the latter. The material of our garments is always formed of substances which have served to cover animals or vegetables.

Warm-blooded animals, more especially, require considerable protection, because the loss of heat suffered by a body increases with the excess of its temperature over that of surrounding space. Thus animals living in cold countries are covered with a thick fur, and the birds with a plumage even more efficacious than the fur. We find in these natural coverings the mechanical division of substances, also bad conductors, pushed to infinity. The thousands of filaments which constitute hair, or make up a feather, oppose a most effective obstacle to the transmission of heat. As to the aerial or aquatic animals, whose bodies have a temperature but slightly superior to that of the medium they inhabit, they have no necessity for clothing; the activity of their vital functions varies with the temperature of the medium in such a manner, that the temperature of their bodies suffers the same changes. These are the cold-blooded animals. Cold stupefies them, because their vital activity diminishes with the temperature; warmth, on the contrary, reanimates them, because their vital activity augments under its influence. A direct relation is established between the interior and exterior conditions.

FIG. 42.—Convection of water.

Liquids conduct heat like solids; but conduction is here habitually complicated with another phenomenon called convection.

3. *Convection of Heat in liquids and gases.*

We have here a glass vessel full of water. and heated from the bottom (fig. 42). A little sawdust is disseminated

through the water, both having about the same density. The particles of wood may be seen to rise in the axis of the vessel, and to descend by the sides. What is the cause of this motion, or continuous circulation? The water heated at the bottom becomes lighter; it therefore rises, and with it the sawdust. As it rises, however, it is cooled, in some degree, by contact with the cooler layers through which it passes, and, arrived at the surface, it is still further cooled by contact with the air, and by radiation. The sides of the vessel are also cooled by the two last mentioned causes, so that the water which touches them is heavier than the water in the central parts. This heavier water falls to the bottom, where it is warmed, and from whence it rises up the centre, and so on as before. The particles of wood follow all the movements of the water, and serve to render them visible.

Convection consists in this displacement of fluid strata thus unequally heated, and it results in the rapid diffusion of heat throughout the whole mass, although the liquid itself may be a very bad conductor; for the warm parts heat the cold parts by contact with them, and this mingling of parts incessantly takes place so long as the vessel remains on the fire. If we wish to observe the conductibility only, we must prevent the transport of heat by convection; and to effect this we have only to heat the liquid from above. Despretz accomplished this by placing on the surface of the liquid a metal box, through which a current of hot water was kept running (fig. 43), by which the liquid column was heated from above downwards. The first layer, on heating, became lighter; it therefore remained on the surface: it heated the next layer lower down by conduction; but this, not being able to heat itself sufficiently to become lighter than the first, remained in its place, and in its turn heated a third layer: and thus the process went on to the end. Several thermometers disposed horizontally down the side of the vessel, as shown in the engraving, indicated, after a sufficient lapse of time, temperatures decreasing from above. Therefore, liquids conduct heat; but they are in general slight conductors. Water, especially, is of very feeble conductibility;

though, for the want of sufficiently precise experiments, this has been long denied. Thus, by putting water in a glass tube,

FIG. 43.—Apparatus to demonstrate the conductibility of liquids.

with some ice at the bottom (fig. 44), the water may be made to boil without melting the ice. But this only proves that the water is of feeble conductibility, and not that it has none at all.

It is much more difficult to prevent convection in gases than in liquids. Currents establish themselves not only in a vertical direction, in consequence of the unequal densities of hot and cold parts, but also in all other directions, in consequence of the expansibility of gases by heat. In all the experiments made on these fluids, the effects produced may be attributed either to conduction or convection. This, however, does not render it the less interesting to observe the effects produced by different gases.

We observed in Chapter III. that the metallic wire

uniting the copper and zinc at the two ends of a Voltaic pile was heated by the interior motion emanating from the pile, which is called the electric current. If the wire be replaced by a series of metallic parts, among which is a platinum wire of sufficient fineness, this last may be heated

FIG. 44.—Water boiling over ice.

to redness. For example, a wide glass tube has the wire fixed in its axis, with the help of copper wire traversing the corks adapted to the extremities of the tube (fig. 45). Each of the corks carries besides a smaller glass tube. These tubes, being open, the air naturally fills the apparatus, envelopes the fine wire, and cools it. This is proved by the fact that, if we close one of the small tubes, and remove the air by the other with an air-pump, we shall see the incandescence of the wire increased.

Now open the little tubes again, and adapt to one of them a bladder filled with hydrogen gas; by pressing the bladder, we shall cause the gas to enter the tube, and thus surround the wire; we shall immediately see the wire lose its incandescence. Therefore, hot bodies are cooled in a greater degree by the contact of hydrogen than by that of air.

It is supposed that conductibility is in the above experiment the principal cause of the difference observed in the behaviour of the air and the hydrogen, and that the latter is the best conductor of all the gases. The effect of the hydrogen gas in contact with the incandescent wire was the same as if the latter had been in contact throughout its entire length with a metal.

When convection is reduced to its least possible activity, the air transmits heat very badly, from which it of course follows that air is but a bad conductor of heat. This property of the atmosphere contributes to the efficacy of furs and other articles of clothing. A stagnant bed of air fills the interstices of their filaments, and arrests the heat. If they were compressed strongly so as to remove the air, they would become better conductors. If this air were not stationary, if it were subject to renewal, it would transmit heat by convection, and the clothing would thus lose its efficacy. This explains why furs are warmer when the hair is turned inwards.

FIG 45 —Apparatus for showing the cooling powers of gases.

The double windows used in cold countries, and in our hothouses, are an application of these principles. Between

the two panes of glass there is a thin stratum of air, which cannot renew itself, and in which the currents are very feeble; it acts therefore like a bad conductor, preventing the heat of the room or hothouse from escaping by conduction. Neither is the heat transmitted by radiation, because glass does not allow the dark rays to pass. As to the solar rays, which are of another nature, they enter freely, and contribute towards the elevation of the interior temperature.

The celebrated Saussure constructed a wooden box, blackened interiorly, one of its sides being formed of three panes of glass separated by thin layers of air. By putting a vessel of water in the box, and exposing the glass side to the rays of the sun, he was able to make the water boil. The explanation of this curious experiment forms a recapitulation of what we have already stated concerning radiation and conductibility. The heat of the sun traverses the glass and the interposed layers of air by radiation, and is readily absorbed by the blackened sides. Being transformed into dark heat, it can no longer traverse the glass by radiation; it is therefore entirely employed in heating the air and water contained in the box. The sides of the box, strongly heated interiorly, keep at a high temperature, in consequence of their slight conductibility, which renders them insensible to the cooling action of surrounding bodies. Finally, the glass surface acts in the same way, in consequence of the two layers of air which remain stationary.

4. *Effects of convection in the ocean. – Marine currents.*

Conductibility plays an important part in the physics of the globe. The distribution of the solar heat on the surface of the earth is more especially effected by convection in the waters of the ocean and in the atmosphere. Immense currents form in the midst of the seas, and give rise to certain laws of temperature, which are as yet but obscurely known. Other currents agitate the strata of the atmosphere at various heights; and these constitute the winds which sweep over our continents, and bring in turn

dryness and humidity, in obedience to laws of which again a few only have been observed.

To understand the manner in which heat determines the marine currents, imagine the terrestrial globe to be entirely surrounded with water. and consider the action of the solar rays on that immense ocean. At the equator, these rays arrive in a direction but little removed from the vertical; as we near the poles, they become farther removed from this direction; and at and close to the poles, they glance across the surface of the earth in a nearly horizontal direction. Their heating effect, therefore, diminishes from the equator towards the poles. In consequence, the superficial layers of water in the equatorial regions have a more elevated temperature than those of the polar regions. The latter therefore descend to the bottom of the ocean, and form lower currents, which travel from the poles towards the equator, and become progressively heated. On reaching the equator, these masses of heated water rise to the surface, and there acquiring a higher temperature, they return towards the poles in the form of upper currents. Thus an incessant circulation would occur in the liquid envelope of the globe, as indicated by the arrows in fig. 46.

FIG. 46.—Theory of Marine Currents.

Now consider the earth as it exists, with its several continents and seas. The form and temperature of the coasts modify the currents which should be established between the poles and the equator. In seas which are nearly land-bound these currents cannot take place, and the local action of the solar rays alone regulates their temperature: thus the water of the Mediterranean is warmer than that of the ocean; the waters of the Indian sea, not having any issue in their northern parts towards the North

sea. This causes a wind called the evening breeze, which lasts as long as there is sufficient difference in the temperature of the land and the sea, and so long as the air is not disturbed by winds due to other causes. It is this evening breeze which the sailor utilizes in leaving a port.

In the morning, when the sun again shines, the same phenomenon occurs, but inversed. The earth gets warm quicker than the sea, and the breeze comes from the sea towards the land: it brings ships into port.

In the same manner mountain breezes may be explained, In the evening we feel in the valley a breeze coming from the tops of the mountains, because there the cooling is most intense. In the morning the wind changes in direction, because the summit of the mountain receives the sun's heat before the bottom of the valley.

Extend our reasoning to large surfaces of country and great masses of air, and we have the explanation of the trade-winds (monsoons), which blow in some countries for six months in one direction, and for six months in the opposite. In the Mediterranean, for example, the wind as a rule comes from the north during summer, and from the south during the winter. We pass over the accidental winds by which the atmosphere is at times disturbed. The summer monsoon is produced by the heating of the Sahara desert, and that of the winter by its cooling; whilst the sea and the southern coasts of Europe preserve a nearly constant temperature. The inequality in the length of the passage between Toulon and Algiers, which is shorter in one direction than in the other, is due to these monsoons. As the heating of the desert is more intense than its cooling, the monsoon from the north is stronger than that from the south, and a sailing vessel which makes the passage regularly in both directions during a whole year takes, on an average, a longer time to accomplish the voyage from Algiers to Toulon than that in the reverse direction.

It will assist our application of these facts to the entire earth if we imagine, as we did in our study of the marine currents, the whole surface of the globe to consist of water, and this again to be surrounded by a stratum of air. It is

at the equator, as before, that the liquid surface is most heated. The air at the equator will, therefore, be lightest, in consequence both of its temperature and of its humidity, which rises with its temperature. If the earth were immovable, this air in rising from the surface would be replaced by colder air coming from the poles, and it would establish a circulation like that represented in fig. 46. In the northern hemisphere there would be a perpetual north wind, and in the southern a perpetual south wind; the two winds meeting at the equator with an equal but contrary motion, would there destroy each other, and there would be a region of perpetual calm the whole length of the equator.

But the earth turns on its axis in one day. Its speed at different points of its surface decreases from the equator to the poles, where it is null. Therefore, as a mass of polar air descends towards the equator, it will pass over a surface which goes quicker than itself towards the east. Let us consider the effects of this.

Suppose that we are stationed on this surface; it would carry us towards the east, and the air which surrounds us would also move in the same direction, but less quickly than ourselves. We should, therefore, traverse and displace it, and the resistance which it would oppose to us would be exactly the same as that of a wind coming from the east. Further, if the air possessed at the same time this movement towards the east, less rapid than ours, and a movement from the north pole towards the equator, its resistance would be that of a north-east wind.

In this manner the diurnal rotation of the earth modifies the circulatory movement of the masses of atmospheric air, due to the convection of heat. In the northern hemisphere we should have a north-east wind; in the southern hemisphere a south-east wind, for a similar reason; and along the equator an east wind, resulting from the combination of the two preceding.

In place of the imaginary liquid earth, let us now consider the earth as it exists with its continents and its seas, the latter, in the equatorial region, covering the greater part of its surface. The same cause for winds will continue to

exist; but a crowd of complications will result from the inequality of the surface, and the winds indicated by our reasoning will not always exist. They are called trade winds. They were observed for the first time by Christopher Columbus, and carried his ship towards America. It is related that his companions were terrified by them, because they feared they should be unable to retrace their steps. We owe the first explanation of these winds to the illustrious Halley.

While the trade winds can be proved to exist on the surface of the globe, it appears more difficult to verify the existence of upper currents, which, predominating in the higher regions of the atmosphere from the equator to the poles, complete the circulatory movement. Their direction should be the reverse of the lower regions; that is to say, south-west in the northern hemisphere, and north-west in the southern. The existence of these winds is proved, however, by the pulverulent matters which they carry from one region to another, and of which the following is a curious example.

In the spring and autumn, a dust may be often collected in France and Italy, coming in the form of a shower, and in which the microscope reveals organic remains from Central America. There are marshes which are dried up at these periods, and which are swept by very violent whirlwinds. They raise the dust of the soil to the height of the upper trade-wind, which, coming from the south-west, transports it towards the north-east, into Europe, in the space of about a month.

We may cite further the case in which ashes and cinders were transported from a volcano in Guatemala, which happened in 1853. The ashes were blown from the west eastwards, towards Jamaica, and were so abundant, that the country was darkened by them for several days.

From all these observations we conclude, that if the convection of heat in the fluid part of our globe is not the only cause of marine and atmospheric currents, it is at least their principal cause. It is only after having thoroughly defined the manner in which this cause acts, that we should occupy ourselves with the consideration of other causes. We then enter the domain of meteorology.

CHAPTER VI.

CHANGE OF THE VOLUME OF BODIES.

1. *Action of Heat on gases.—Sensible Heat.—Exterior work.*

PLACE a well-closed bladder nearly filled with air near the fire; it will gradually expand, and at length burst. And yet the quantity of air it contains remains the same, because communication is not possible between the interior of the bladder and the atmosphere. At the same time the bladder becomes somewhat heated, and if we tie its neck round the tube of a thermometer (fig. 49), placing the bulb in the centre, we shall see that the temperature of the interior air rises. Remove the bladder from the fire; it will contract of itself, and, growing cool, will resume its former condition. Thus, in absorbing heat, the air in the bladder has undergone two modifications, an elevation in temperature and an augmentation in volume. In losing heat it, on the contrary, suffers a diminution both in temperature and volume. The change of temperature is easily understood: it is neither more nor less than the manifestation of the property possessed by all bodies of being heated or cooled, of changing their calorific state by absorbing or disengaging *sensible heat*, and this term we shall always employ to designate heat which is appreciable by the thermometer. But the change of volume is a different matter, which we shall now proceed to consider.

The bladder is pressed interiorly by the air it contains, and exteriorly by the atmosphere, and as it is very flexible, and not elastic, we must admit that the two pressures are in equilibrium. When it is heated, the interior pressure

is augmented at the same time as its sensible heat; and this augmentation may be measured by the height to which the liquid column is raised. As to the bulk of this air, it is increased to an extent equal to the volume of the oil raised in the tube, and to that which corresponds to the expansion of the flask. We have therefore demonstrated the following property of gases: When a gas is heated without its volume being allowed to change, its elastic force increases at the same time as its temperature.

FIG. 51.—Heating of a gas, its volume remaining the same.

Generally, this increase of elastic force is not so visible as in the preceding experiment. Take, for example, the apparatus represented by figure 1, which consists of a hollow copper ball, mounted on wheels. Stop the opening tightly, and light the spirit-lamp beneath. The air in the ball will now be heated, whilst its volume is as nearly as possible unaltered. It presses the sides of its prison at all points; but they resist, and nothing makes this pressure visible. As soon as the temperature rises to about 272°, each square centimetre of the internal surface will be subjected to a pressure from within equal to a force of more than two kilogrammes, whilst on an equal extent of the outside surface the atmosphere exercises a pressure of only one kilogramme. If the stopper exhibit a surface of one square centimetre, it will therefore be now submitted to a pressure of one kilogramme from within; and in consequence, if it is not firmly fixed in the orifice, it will be thrown out, and the apparatus will recoil, as already explained. If the stopper be fixed more firmly, the temperature must be raised higher; the elastic force will increase, and

may become sufficiently great to make the stopper fly out. We shall have a proof of this increase in the force of the recoil, which becomes greater as the temperature rises higher at which the explosion occurs.

This experiment explains explosions that take place under a number of circumstances. In most cases these are due to inflammable substances being contained in a closed space. The combustible takes fire, accompanied by chemical combination, and the disengagement of heat and light. The mixture becomes intensely hot, and there is no room for it to expand. Its elastic force increases rapidly, until at last it overcomes the obstacles opposed to it. When this takes place, the gases rush out with violence; and the disturbance thus occasioned is the cause of the noise we hear.

Explosion may also take place without the intervention of the air; for example, with gunpowder, because the substances which compose it become transformed into gas, as we have seen in the first chapter.

When a gas is heated, its volume being kept constantly the same by confinement in a close place, the heat is only employed to give its molecules a particular activity, which is manifested by an increase of elastic force and sensible heat; it must not be supposed that the increase in elastic force is a mechanical work which consumes heat. The heat produces only a single effect, which is elevation of temperature, and there is no work done, because, in the modification which the gas undergoes, no resistance is overcome by force. To say that the heated gas presses the sides of the vessel more than the cold gas, is to say that the heat it acquires augments its expansibility; there is no resistance overcome here, as in the case of the gas being heated under a constant pressure. The sensible heat supplied to the gas gives it an expansive property, which would serve to measure this heat, as well as its action on the thermometer. It may be said that expansibility and temperature in a gas are two forms of the sensible heat which it contains.

We therefore arrive at this second rule relative to the heating of gases: When a gas is heated, its volume remaining

constant, all the heat it receives remains in the gas in a sensible state, and serves to elevate its temperature: this elevation in temperature is accompanied by an increase in the pressure against the sides of the enclosing vessel, and is neutralized by their resistance. Reciprocally, when a gas is cooled, its volume remaining constant, it loses a part of its sensible heat, which passes into exterior substances, the temperature and pressure falling simultaneously.

From our two rules we may draw the following consequence. To raise the temperature of a kilogramme of air from zero to 272 degrees, it would be necessary to consume a larger quantity of heat, if the air dilated whilst preserving the same pressure or elastic force, than if it were kept at a constant volume; because in the first case heat is expended to effect a mechanical work which does not take place in the second. This conclusion is confirmed, in fact, by abundant experience.

Gases are most often heated under such circumstances that there is a simultaneous change in volume and pressure. The quantity of heat which they consume then depends both on the elevation in their temperature, and on the mechanical work put in play. Everything else being equal, it therefore varies with this work. A kilogramme of gas consumes when rising in temperature, to a certain extent, and reciprocally disengages, when falling. different quantities of heat, according to the mechanical effects which take place. When the volume of the gas augments, a mechanical work is produced, and a certain amount of heat disappears; when it diminishes, the mechanical work is spent, and heat appears. We have discussed the relation between heat and work whilst occupied with the mechanical equivalent of heat.

The principle enunciated above explains how the hot-air engine produces work by the consumption of heat. Whilst dilating, the air contained in the machine produces work; whilst contracting, the same air expends work, but less in amount, the difference between these two being the part utilized. Further, in the former case heat is consumed, and in the latter a less quantity is disengaged; the difference

between these two quantities of heat is destroyed, or rather converted into work.

2. *Action of Heat on solids and liquids.—Grandeur of molecular forces.—Interior work.*

The action of heat on solids and liquids is more complicated than its action on gases, because the molecules are held together with considerable force. Imagine a mass of iron heated in the midst of the atmosphere. It expands and produces a preliminary mechanical work analogous to that of the vessel filled with air which was under consideration at the commencement of the present chapter. A cubic decimetre of this substance, heated from 0° to 100° C., increases in volume scarcely four cubic centimetres: if this mass of iron have the cubic forn, each edge lengthens about twelve-hundredths of a millimetre. The atmosphere exerts over each of the six faces of the cube, a pressure of 103 kilogrammes, and this is the measure of the exterior resistance which the heat must surmount in order to expand the body. The total work produced is the displacement, by six-hundredths of a millimetre, of six times 103 kilogrammes, a quantity less than one-tenth of a kilogramme. As we know that each thermal unit is equal to 425 kilogrammetres, we may conclude that the heat consumed by overcoming the resistance of the atmosphere in the phenomenon under consideration is very small, and need not be taken into account. But we shall find a second kind of work which we did not meet with in gases.

The molecular forces in solids and liquids may, without exaggeration, be called stupendous. Experiments made on the elasticity of solid substances show that, to lengthen by twelve-hundredths of a millimetre the side of a cube of iron one decimetre in length, requires a force of about 250,000 kilogrammes. Such would be the exterior force necessary to overcome the resistance of the molecular forces.

Now that which requires this enormous mechanical effort heat effects naturally, and at the same time raises the temperature of the cube of iron from 0° to 100° C. It therefore

overcomes the resistance of the molecules of iron, and separates them after the manner of a veritable force, thus effecting an *interior* work capable of being expressed in kilogrammetres. Each time 425 kilogrammetres are thus produced in the interior of a body, one thermal unit will have been expended, for which we shall not be able to account in the amount of sensible heat possessed by the body.

We have another proof of the grandeur of the molecular forces in the enormous mechanical efforts developed by the expansion and contraction of solid and liquid substances when they undergo a change in temperature.

In making a cart-wheel, the workman heats the iron hoops so as to expand them, when they pass over the wheel very easily, and are allowed to cool: the contraction of the tire causes it to bind the wheel with great force.

The iron rails laid on railways are not fitted closely end to end, but are always separated from each other by a small interval, so that they may be able to expand freely in their length. Without this precaution they would bend during the heats of summer. In fact, if the rails were close together over a length of 250 miles, the total change in length, from winter to summer, would be over 900 feet; and, as the sleepers fix them firmly to the soil, they could not suffer such a change without twisting out of shape.

Again, it is the force of expansion or contraction which causes the rupture of substances which are bad conductors of heat, when they are subjected to a sudden change of temperature. For example, if you touch glass with a piece of red-hot iron, the glass breaks. It is because the parts touched expand rapidly, and the neighbouring parts remaining cold obstruct the expansion; they are roughly repulsed in every direction, so to speak, and separate from each other. The same effect would take place if the glass were touched by a substance excessively cold; but in this case the rupture would be due to the rapid contraction of the molecules. The possibility of breaking cold glass by the contact of a very hot substance is utilized in cutting glass vessels. A mark is made on the glass with a file, and a

piece of red-hot charcoal applied to it; the rupture takes place in the direction of the mark; the charcoal being then drawn along just in advance of the crack, and in the necessary direction: and the glass may be cut in this direction if it has no irregularities of structure.

To observe the force of expansion in liquids, a vessel made of glass, or other resistant material, may be filled with the liquid upon which we wish to operate, closed hermetically and heated; the vessel will be broken if the cork be quite tight.

Take an iron vessel, having somewhat the shape of a bottle or flask, and holding about a quart; fill it with water and close it with a screw stopper, then heat it to boiling point. The expansion of the iron vessel will barely amount to a quarter of a cubic inch, whilst the water will increase in bulk more than two and a half cubic inches, about ten times more than the vessel. This water will therefore exercise an enormous pressure on the iron which encloses it, distorting its shape, and finally breaking it, if it be not sufficiently strong.

A very curious application of the force of contraction of solids has been made by the architect Molard, on the building of the *Conservatoire des Arts et Métiers* in Paris. The walls of a vaulted gallery had been pushed outwards by the weight of the superincumbent masonry, and it was feared the whole would fall. Molard arranged iron bars in a parallel direction, passing through the walls, and carrying at both ends a screw thread fitted with screws (fig. 52). He heated the bars throughout their whole length, and having immediately screwed them up tight, allowed them to cool. The contraction of the iron, which proceeded slowly as it cooled, drew the walls nearer together without endangering them; and this was repeated several times, until the walls were re-established in a vertical position. The bars were left to maintain them so, and may be seen to the present day.

The laws of the dilatation of metals deserve the more careful study, seeing that iron especially is now so generally used for building purposes. A serious question might be raised, whether its universal employment is not in some

measure censurable; whether, in fact, our houses and public buildings are not exposed to accidents owing to simple change of temperature. The roofs of zinc or lead, constructed of sheets of metal joined together, warp in the

FIG. 52.—Straightening of the walls at the *Conservatoire des Arts et Métiers.*

summer because their expansion is confined by the fastenings, and tear apart in the winter because their contraction is hindered. It is therefore advisable to make one sheet overlap another, much in the same manner as tiles, so that the metal may freely undergo the changes of dimension to which it is subjected. It is equally necessary that gutters which are exposed to the air, should not be soldered together in too great lengths. Strong stones have been broken by the expansion of bars of iron fastened into them. The stones even, although their expansibility is not great, sometimes separate from each other in very cold weather, and again close up when it becomes warm. In bridges a lowering or elevation of the arch results from the same causes. Suspension bridges are, above all, peculiarly liable

to these dangerous alterations of expansion and contraction. A chain of 100 yards long suffers in one year a variation of about two inches and a half. These effects must all be taken into consideration in the construction of buildings; and, above all, materials expanding unequally must be kept separate, because it is the unequal expansion of different parts which oftenest causes the greatest danger to the whole.

After having thus demonstrated by so many observations the power of the molecular forces which exist in solid and liquid substances, we conclude that heat, in overcoming the resistances of these forces, produces an interior mechanical work, and that it is partially spent or consumed in the operation, according to the following rule:—

When a solid or liquid body is heated, and it expands whilst overcoming an exterior resistance, such as that of the atmosphere, the heat consumed may be divided into three parts: the first is expended to produce an exterior work, the second to produce an interior work; the third, passing into the body, remains in a state of sensible heat and causes an elevation in the temperature.

If the body which has been heated is afterwards cooled, the heat which it disengages comes from the three preceding operations, effected inversely: a part is created by the exterior resistances when they press on the surface of the body, and compress it little by little. Another part is created by the molecular forces, as they draw the molecules nearer to each other, and replace them in their primitive positions. The remainder of the heat disengaged is the sensible heat of the body, which passes outwards at the same time that the temperature falls. In the first operation an exterior mechanical work is expended, and in the second an interior work.

It is the existence of the interior work which establishes an essential difference between gases and solids or liquids. Generally these last-named bodies are not subjected to other exterior pressure than that of the atmosphere, and then the exterior work may be disregarded: the heat corresponding to the interior work (which is called heat of expansion) and the sensible heat, only are considered.

3. *How the expansion of bodies is measured.—Maximum density of water.*

We shall now proceed to show how the expansion of bodies may be measured. To attain this it is necessary to invent delicate and extremely sensitive instruments.

For gases, the most simple instrument has the form of Galileo's thermometer (fig. 6, A.) By weighing the amount of mercury necessary to fill the bulb, and that which occupies one division of the tube, we may calculate by proportion how many times the bulb contains the capacity of one division. Then, having introduced the gas into the bulb, and a little mercury into the tube so as to separate the gas from the atmosphere, we shall know how many divisions correspond to the volume occupied by the gas. When the bulb is placed in water by the side of the thermometer, and the water is heated, we may see the little mercurial index move, and the number of divisions it passes through measures the expansion, whilst the thermometer measures the number of degrees that the temperature rises. We may thus prove the law of Gay-Lussac: for each degree, the volume of any gas whatever increases by $\frac{1}{272}$ of its original volume.

The same apparatus will serve for liquids. We have only to fill the bulb with the liquid, as in the construction of the thermometer, and to follow the same rules as with gases.

In all cases the expansion of the glass must be taken into account, as it makes the increase in the volume of the gas or liquid in the bulb appear too small. We may convince ourselves of this fact by performing the following experiment.

Take a glass flask, to the neck of which is joined a tube divided into equal parts, and fill it with alcohol, coloured red, so as to form a kind of enlarged thermometer (fig. 53). If we plunge the flask into boiling water, we shall immediately see the level of the spirit fall; but later it rises, and ascends higher and higher. To explain this:—The glass which incloses the liquid becomes hot first; it therefore expands, and more room being thus provided, the level of

the spirit sinks. But, gradually, the liquid also becomes heated, and, as it expands more than the glass, its level rises, not only to, but above its original position.

It is by paying attention to this effect of the vessel in which they were contained, that the *coefficient of expansion* has been measured in several liquids; that is to say, the quantity by which the unity of volume increases when its temperature is raised one degree, and it has been found that they have not the same coefficient. Thus alcohol expands more than water, and ether more than alcohol.

FIG. 53.—Apparent Expansion of Liquids.

We may remark here that any body whatever that has been expanded by heat, contracts according to the same law in the inverse action of cooling; that is to say, it always resumes the same volume in passing through the same temperature.

Water presents a peculiar phenomenon, which finds an important application in nature.

Take a large water-thermometer, similar to the last-mentioned flask, plunge it into water having a temperature of 46° Fahrenheit, and let it remain in the water until it also is at this temperature; we shall see the level stop at a certain division of the tube, which we shall mark. Now immerse a few pieces of ice in the water-bath, so as to cool it: the level of the water will descend in the tube as the temperature falls; soon, at about 39°, it will appear stationary, but will again rise, and when the bath has fallen to 32° the level will have returned to nearly its primitive position. Thus the water inclosed in our large thermometer is at its smallest possible bulk when at a temperature of 39°.

We conclude from this that water at 32° Fahrenheit, when heated, first contracts, reaching its smallest volume when at 39°, and afterwards expands more and more until it begins to boil.

There is, therefore, more water in a quart measure at 39° Fahrenheit, than at any other temperature; which we express by saying that water attains its maximum density at 39° Fahrenheit. It is in consequence of this peculiarity that the kilogramme has been fixed on as the weight of a litre of water at this particular temperature,* and not at an indefinite temperature.

The celebrated Saussure has noticed that the temperature at the bottom of deep lakes is 39° Fahrenheit (4° Centigrade) in all seasons; we now know the reason. During the autumn nights, the surface of the water of the lakes is cooled; and as it becomes denser, it sinks, and the lower and warmer parts rise to be cooled in their turn. As the water is most dense at 39° F. it follows that the parts which have fallen to this temperature should sink below all the rest,—that is to say, to the bottom. There is, therefore, a descending current of cold water and an ascending current of warmer water, so that the temperature decreases progressively from the surface downwards, and is always at 39° F. at the bottom. When in the day-time the sun's heat reaches the lake, the upper parts in becoming warm become less dense, and remain in their place; further, they absorb the solar heat and prevent it from reaching the water at the deeper parts of the lake. As colder weather approaches, the nocturnal cold becomes predominant, and at last the whole bulk of water in the lake will have fallen to 39° F. On the arrival of winter the surface-waters become colder than 39° F., but at the same time becoming less dense, they still preserve their position. The temperature increases downwards from the surface (where it may be at 32° F., 0° C.) until it reaches the bottom, where it is always at 39° F. When the surface-waters fall to zero (32° F.) it begins to congeal slowly, little needles of ice form, and float, because they are less dense than the water. Agitated by the wind, they increase in size by congealing the water that they touch, and at last they join together and form a sheet of ice which covers the lake. This glacial covering preserves the lower waters from

* Namely, 4° Centigrade, or 39° Fahrenheit. In England the standard gallon of water weighs 10 lb. at a temperature of 62° Fahrenheit.

cooling, and thus their temperature is maintained throughout the winter. On the return of warm weather the ice melts; so long as the water produced is at zero, it remains at the surface; it is not until after some time that it receives sufficient heat to attain the temperature of 39° F., but there is a moment when the water throughout the whole extent of the lake will again have this common temperature. In the summer the upper parts are warmest, and if the lake be sufficiently deep they will prevent the solar heat from penetrating to the bottom. The lower parts are again but slightly heated by conduction, because water is an extremely bad conductor of heat. To sum up, thanks to the maximum density of water, heat is, as it were, stored up at the bottom of lakes and seas. It there maintains in existence an infinity of beings, animal and vegetable, which have not therefore to combat either excessive heat or cold. In this provision we see an evidence of admirable order, and the fact, which at a first glance appeared anomalous, reveals itself as the principle of a grand terrestrial law.

There is no delight more pure than that of the man who, after having habituated his mind to reading the book of Nature, is allowed to contemplate its beauties. The traveller tastes this pleasure when, face to face with a grand spectacle which he has sought at the price of a thousand fatigues, he reflects on the cause of the marvellous effects on which he contemplates, and raises his mind sufficiently to discover the law dictated by the Creator. And when he has seized this law there are no longer useless details for him; he finds in the smallest fact which escapes the attention of the listless a verification of the justice of his reasoning. In this spirit, Rumford, traversing the glaciers of the Alps, stopped before a natural cavity like a small pit dug in the ice. He perceived a stone at the bottom of the water which filled this cavity, and in the following manner explained how the pit had been sunk. The stone, resting in the first place on the surface of the ice, absorbs the heat of the sun better than does the ice, and thus melts a small portion of the latter which surrounds it. The water arising from this fusion then becomes heated to 39° F. (4° C.), and

sinks to the bottom of the cavity thus commenced. By giving up some of its heat, it there causes a fresh portion of ice to melt, and thus enlarges the cavity. Having then become less dense, it again rises to the surface, is again heated to 39° F. by the sun, and afterwards sinks to the

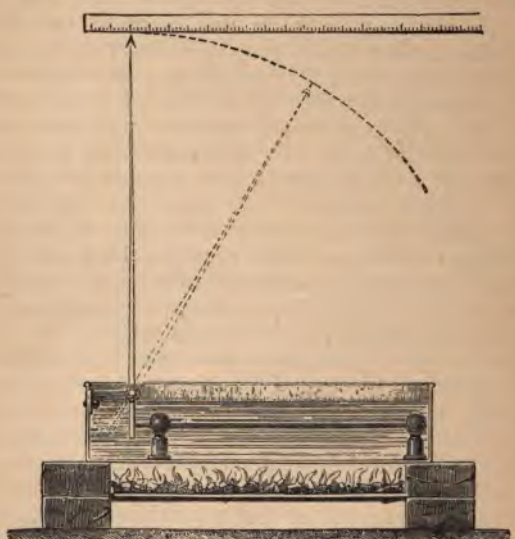

FIG. 54.—Apparatus for measuring the Expansion of Solids.

bottom, and thus continues the formation of the cavity. The pit has thus been gradually sunk by this circulation of water taking from above the heat of the sun, and carrying this heat below to the ice. The stone remains at the bottom as a silent witness to the circumstances which have produced the hole.

We have still to study the methods of rendering the expansion of solids measurable. It is so small that special instruments are necessary to measure it. Thus, we have stated that a decimetre of iron lengthens by about twelve

hundredths of a millimetre when it is heated from zero (32° F.) to 100° C. (212° F.): this excessively small expansion may be rendered measurable in the following manner:

An iron bar one metre long is placed in a large reservoir; one of its extremities rests against a fixed obstacle, whilst the other is brought to bear on the short arm of a vertical lever (fig. 54). The long arm of the lever is a thousand times longer than the short one, and its motion is measured by a horizontal divided rule. The bar of iron is surrounded by ice, and the point marked by the indicator on the rule is observed. The ice is now taken out, and water put in, which is made to boil by heating the bottom of the reservoir. The water boils, and the bar of iron is therefore heated to 100° C.,* and consequently the point of the lever advances twelve decimetres along the horizontal rule. Evidently, the expansion of a bar of iron is a thousand times less; that is to say, the increase in length amounts to twelve-tenths of a millimetre. It may be easily discovered by means of this apparatus, that the expansion is 100 times less for one degree; the coefficient of the linear expansion of iron amounts to $\frac{12}{100000}$ of its length at zero.

If the bar of iron be replaced by one of another substance, a different number will be obtained: each substance has its particular coefficient of expansion.

It is easy to demonstrate the unequal expansibility of two metals by making a straight bar with a blade of copper, and one of iron, for instance, riveted together (fig. 55). When this bar is heated it becomes curved, and the copper is on the convex side. It therefore occupies a greater length than the iron. When allowed to cool, the bar will again become straight. If again it be exposed to very great cold it will curve in the reverse direction, and the copper, contracting more than the iron, will be found to occupy the concave side. It has been thought possible to construct pyrometers founded on this kind of effect.

The increase in volume of a solid substance caused by heat may be deduced from the increase of length suffered by a bar of the substance. Thus, a bar of iron one deci-

* The boiling point of water is 100° on the Centigrade thermometer

metre in length, lengthens $\frac{12}{1000000}$ of a decimetre for each degree in the elevation of its temperature; a cubic decimetre would therefore expand for each degree three times the amount.—that is to say, $\frac{36}{1000000}$ of a cubic decimetre, or

FIG. 55.—Double bar (iron and copper).

thirty-six cubic millimetres. This result may be demonstrated by reasoning, and its exactitude proved by experiment with the help of peculiar apparatus, which, however, need not be described here.

4. *Explanation of various phenomena.*

One very curious effect of the expansion of solids may be observed by almost any one. It was discovered in 1805, in a foundry in Saxony, by M. Schwartz. A very hot ingot of silver had been placed on a cold anvil, and it began to tremble, producing at the same time a musical sound. This phenomenon was again observed in 1829 by Mr Trevelyan, in England, when he happened one day to rest a very hot soldering iron on a mass of cold lead. Professor Tyndall has repeated the experiment in the following manner:—

Two thin plates of lead are fixed in a vice parallel to each other; but kept separate by a piece of wood one centimetre in

size (fig. 56). A fire-shovel is then heated and balanced on the edge of one of the plates of lead. It will then oscillate from one bar to the other, and a sound will be heard which may be made very pure if the handle of the shovel be lightly supported with the finger.

We will now explain this phenomenon.

The lead is warmed at the point of contact with the shovel; it expands at this point, and a little elevation is

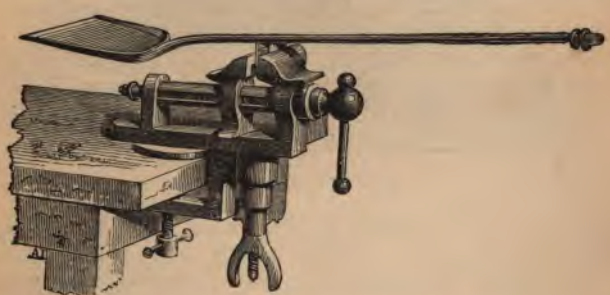

FIG. 56.—Trevelyan's Experiment.

caused suddenly, which makes the shovel *see-saw:* it falls against the second plate, where the same effect is produced; the shovel therefore returns to the first, and oscillates so long as it remains hot enough to cause a sufficient elevation in the piece of lead it touches. This oscillation is a vibratory motion, which is propagated in the air until it reaches the ear, where, if sufficiently rapid, it will produce the sensation of sound. The pitch of the sound is higher as the oscillations are quicker.

Mr Gore has made another experiment, which may be explained in the same manner. Two copper rails are placed at a distance of two centimetres from each other on a wooden stand, so that a hollow copper ball may roll easily along them (fig. 57). A copper wire is attached to the extremity of each rail, the two wires being connected with

the poles of a Voltaic pile. The electric current passes through the rails and the ball of copper, and heats the rail very strongly at its point of contact with the ball, because at this point the resistance to the passage of the current is very great. A little elevation is therefore caused,

FIG 57.—Gore's Experiment.

and the ball is raised; it is therefore no longer in equilibrium, and at first vibrates a little, but a new elevation being formed at each fresh point of contact, it begins to roll.

It may very naturally be asked, if all solid substances expand by heat. We have seen water contract when heated from zero to 4° C. (39° F.), and it is natural to suppose that there may also be solid substances which behave in a similar manner. In fact, wood and certain argillaceous earths contract by heat: but that is caused by the water interposed between their particles, which evaporates when heated, and allows the particles to come nearer together; solids of this kind often have pores sufficiently large to contain much water. Their contraction by heat does not, therefore, resemble that of water at zero. Lately, it has been discovered in England that vulcanized caoutchouc really contracts by the action of heat on its molecules, when it is stretched out strongly and it possesses all its elasticity. This property evidently depends on the position of the molecules, which may be such that heat *them nearer* together, disarranging them and over

the interior forces which unite them. The molecules of ordinary unstretched caoutchouc are arranged differently from those of stretched caoutchouc; it is not, therefore, astonishing that, both being heated, the first should expand while the other contracts: this results from the different arrangement of their molecules.

Yet another property of bodies relative to the change in their temperature remains to be noticed. We have already alluded to it in our study of conductibility, but it is one which demands more particular attention.

5. *On specific Heat.*

Take a block of ice, and make two cavities in it. Put in one 80 grammes of water at 100° C., and in the other 80 grammes of copper, also at 100° C. You will find, after some time, that the ice melted by the hot water weighs 100 grammes, whilst only a tenth of this quantity is melted by the copper.

Thus copper, in falling from the same temperature as an equal weight of water, disengages one-tenth of the amount of heat. Reciprocally, we may say that, in being heated the same number of degrees as an equal weight of water, it will consume one-tenth only of the amount of heat.

If another similar experiment be made, putting in the cavity 80 grammes of water at 50° C. (instead of at 100°), only 50 grammes of ice will be found melted (instead of 100 grammes), so that the quantity of heat disengaged by a certain weight of water falling from 100° C. to zero, is double that disengaged by the same weight of water falling from 50° C. to zero. This quantity of heat is proportional to the falling temperature, and it is the same when the operation is reversed, and the heat is under consideration which corresponds to an elevation of temperature. It results from this reasoning, that if we give the name thermal unit to the quantity of heat necessary to raise from zero one kilogramme of water one degree, two thermal units will be necessary to raise it two degrees, 100 thermal units to raise it from zero to 100° C. Now, if instead of one kilogramme

CHAPTER VII.

ON FUSION AND SOLIDIFICATION.

1. *Law concerning the temperature at which substances fuse—Heat consumed during fusion and produced by solidification.*

We have shown in our second chapter that if a thermometer be plunged into ice which is being melted by the application of heat, it will not mark any change of temperature so long as any ice remains; and, keeping before us the proper definition of the word, we say further, that the temperature of melting ice is constant. This property, in fact, belongs to all other substances which melt by the action of heat. To illustrate this, heat some sulphur in a glass flask (fig. 58) and immerse the bulb of a mercurial thermometer in it. We shall see the level of the mercury rise gradually until it indicates 110° C. on the scale, when fusion commences. After this, the mercury will not rise until the whole of the sulphur is completely fused into a liquid mass. The fusing point of sulphur is said to be 110° C.

Again, take liquid sulphur at 120° C. of temperature, and allow it to cool. At first the level of the mercury in the thermometer will fall, but having reached 110° C. it will stop, and at the same moment solid needles of sulphur will appear on the surface of the molten mass and on the sides of the vessel which contains it. In fine, the sulphur has resumed the solid state throughout, and its temperature has remained constant during the solidification. This temperature is the same as that of fusion. The level of the

thermometer will not recommence descending until the solidification is complete.

A great number of substances present the same phenomenon; only each has its special point of fusion or solidification. Thus bees'-wax melts at 62° C., tin at 235° C., lead at 332° C., gold at 1,200° C.

There are infusible substances. Some, like carbon, resist the highest temperature one can command, and are hence called refractory; others, like white lead, marble, and wood, are decomposed by the action of heat, because their atoms are feebly united. The number of the first-named class diminishes as the progress of science gives us the command of higher temperatures; as to the second, we are enabled to fuse some of them by submitting them to a strong pressure so as to prevent the separation of their atoms. Marble has thus been melted by inclosing it in a gun-barrel hermetically closed by a screw stopper. When the marble is heated under these conditions, it at first undergoes a partial decomposition, carbonic acid gas and lime being produced. The gas being imprisoned in the gun-barrel exerts pressure on the unaltered marble, and maintains its elements in union—this may now fuse. After a sufficient lapse of time the apparatus is allowed to cool, and, on opening it, appearances of fusion will be found in the solid residue.

FIG. 58.—Fusion of Sulphur.

In order to solidify a liquid by cold, only one difficulty has to be surmounted: the cold must be sufficiently energetic. As the means of producing intense cold become better understood, we shall be able to solidify many substances which at present baffle our skill. Mercury solidifies at 40°, and protoxide of nitrogen at 100° below zero of the

Centigrade thermometer. We shall see in Chapter IX. that these are the substances used for the production of excessive artificial cold. Among the liquids which we are still unable to solidify, may be mentioned the sulphide of carbon, a substance which is much used in the manufacture of caoutchouc. The complete fusion of solid substances does not always occur suddenly, as in the case of ice and sulphur, which become as fluid as possible at the instant of melting. Glass, for example, assumes a pasty consistence when its temperature is sufficiently high, and it is whilst in this state that it can be fashioned by the glass-workers, drawn into thread, blown, bent; in a word, worked into a infinity of shapes. Also, alcohol, when subject to excessive cold, becomes viscid. The pasty condition does not always appear at or about the temperature of fusion; it results from a particular arrangement of the molecules, and in some instances takes place at other temperatures. This is the case with sulphur, which becomes pasty at about 200° C.

It will be worth our while to give a few moments' attention to the leading phenomenon described above; namely, the constancy of the temperature of fusion and solidification, with a view to discover the part played by heat in these operations. When a body melts, its molecules are evidently separated one from another by the action of heat derived from some neighbouring body. As these molecules were bound together by interior forces, it was necessary to overcome the resistance of those forces; hence, so much interior work produced and heat spent. From the fact that the temperature remains constant, we should conclude that the heat which reaches a substance undergoing fusion does not enter it in the state of sensible heat, but is transformed as it enters into a mechanical work. This work is interior only if there is no outside pressure acting on the surface of the body so as to hinder the change in volume which always accompanies fusion. If, on the contrary, such a pressure exists,—that of the atmosphere, for instance,—the exterior work must be taken into consideration; but usually this is so slight compared with the interior work, that the latter may be said to exhaust all the heat supplied. The

heat thus expended is usually called *latent heat;* but as such an expression, used in former days by the believers in caloric, might suggest that this heat really exists, hidden somewhere in the body, we prefer to call it by a name which simply expresses the observed fact,—namely, *heat of fusion.*

In the inverse operation, that of solidification, the constancy of the temperature is now very easily explained. The fluid molecules being subjected to cold, cease to be separated from each other by heat so soon as their temperature falls to the point of fusion; the interior forces, no longer overcome, are again victorious, and reconstitute the solid body. In resuming this condition, mechanical work is expended, and an equivalent of heat is created. It is this heat which, being gradually disengaged, prevents the sensible heat of the body from diminishing, and, in consequence, the temperature from falling. After solidification a quantity of heat should be disengaged equal to the heat spent during the fusion the exterior work being neglected in our estimate. The following experiments will prove the exactitude of this reasoning.

We already know the heat of fusion of ice: to melt a kilogramme of ice at zero would require a kilogramme of water at 79° C. This water is cooled as the ice melts, and it falls to zero, after which it ceases to act. At each degree of its fall in temperature it disengages one thermal unit; the total heat consumed by the fusion of one kilogramme of ice at zero would therefore amount to 79 thermal units. The same result would be obtained by replacing the kilogramme of water at 79° C. by 79 kilogrammes at 1° C. of temperature.

A similar experiment may be made with wax, which melts at 62° C. Take a large quantity of bees'-wax maintained at this temperature, without being allowed to fuse, and throw over it 44 kilogrammes of water at 63° C.; the temperature of this water will fall to 62°, disengaging 44 thermal units, and one kilogramme of wax will be found melted. Thus the heat of fusion of wax is 44 thermal units, rather more than half that of ice.

It is equally easy to prove that solidification is accom-

panied by the disengagement of heat. Lead melts at 332° C. Maintain exactly at this temperature one kilogramme of the metal in the solid state; to do this it is simply necessary to reduce the supply of heat at the instant that the metal has attained a temperature of 332° C. to no more than may be sufficient to prevent the lead from cooling. Throw this lead into one kilogramme of water at zero, the temperature of the water will rise ten degrees. Therefore the kilogramme of lead in cooling has disengaged ten thermal units. Make another experiment with one kilogramme of lead completely *melted* and at the same temperature of 332° C., and throw it into one kilogramme of water at zero; the temperature of the latter will rise fifteen degrees. This increase of five degrees indicates a disengagement of five thermal units, which did not occur before. It occurs because the kilogramme of melted lead first solidifies by contact with the cold water before cooling, and disengages a quantity of heat equal to that it had absorbed from the fire whilst melting. The conclusion from this double experiment is, that the heat of fusion or solidification of lead is five thermal units, sixteen times less than that of ice.

Every fusible substance has its peculiar heat of fusion, and, what is remarkable, ice requires the greatest quantity of heat to melt it, as it also has the greatest capacity for heat. In accordance with these facts, it comes to pass that the frozen soil in winter receives a store of heat, which tempers the cooling action of the atmosphere and the celestial space, and which prevents the temperature from falling rapidly below the freezing-point, because each kilogramme of water which freezes disengages seventy-nine thermal units. When a thaw occurs, the water again takes up this amount of heat, and in so doing tempers the warming action of the atmosphere and the sun; it prevents the temperature from rising rapidly above the freezing-point—another cause, in addition to those we have before alluded to, of the mildness of the climate in regions which abound in water. Cold and warmth thus succeed each other less suddenly; there are not, as in countries deprived of water, like Central Asia and Australia, excessive cold in winter and excessive heat

in summer. Water, therefore, may be called the natural regulator of temperature on the surface of the earth.

The slow melting of ice is a consequence of the fact that this substance requires a great amount of heat to melt it. Thus a layer of ice on the surface of a body is often very efficacious as a protection against heat: the temperature of the body cannot rise above the freezing-point until the whole of the ice is melted. Inversely, a layer of water acts as a preservative against cold in consequence of the slowness of its congelation. Envelope a body in wet rags, and keep the latter soaked with water, you will prevent the body from cooling below the freezing-point, even if exposed to a very sharp cold; the water will form little icicles slowly on the linen, whilst continually disengaging heat. This method is available for the preservation of organic substances from frost during winter.

Some curious examples are on record, illustrating the slowness with which ice melts. In the winter of 1740 a palace was constructed in St Petersburg of ice taken from the Neva in large blocks. As gay parties were assembled in this palace, evidently a large quantity of heat must have been accumulated within, which slowly melted the superficies of the walls; but the fusion was very slow, and the walls being sufficiently thick, lasted for a long time. Cannon, with barrels four inches thick, were also made of ice, from which iron bullets were fired, yet the cannon were not melted nor broken by the explosion of the powder. In Siberia sheets of ice are used for windows; their interior surface does not melt, because the outside is so excessively cold as to keep the temperature of the whole below freezing-point.

What we mean by heat of fusion is sufficiently exemplified by the facts just stated. We have now to seek experimental proof of the interior work effected in the operations of fusion and solidification.

2. *Interior Work.—Crystals.—Ice-Flowers.*

Melt some sulphur in a large earthen crucible, and allow it to cool without agitation. It will cool very slowly, and

the temperature will fall to 110° C., first on the surface and on the sides of the crucible, the central part still remaining liquid after the solidification has commenced. Little needles of sulphur will be seen to form on the surface, crossing each other in all directions. At this moment, break through the centre of the crust thus being formed, and turn the crucible over; the liquid sulphur will run out, and the solidified part be found adhering to the sides in the shape of delicate yellow transparent needles, all pointing towards the centre of the crucible (fig. 59). These are called crystals of sulphur, and by carefully studying their form it has been discovered that each crystal is terminated by plane faces regularly disposed.

FIG. 59.—Crystallization of Sulphur.

A law therefore presides over the arrangement of the molecules; when solidification takes place there are motive forces which cause each molecule to take a determinate position. But the movement of a molecule under the influence of a force is a mechanical work expended; and the whole of these molecular movements constitute what we call interior work. We have, therefore, proved the existence of this work by arresting it whilst under execution, and by showing the interior state of the body at that moment. If we had allowed the sulphur to cool entirely, this work would have been continued silently, hidden by the superficial crust, and the admirable structure presented by the interior would have escaped our notice. The molecular forces are consummate architects, always working in obedience to laws dictated by the Creator.

It is not always easy to crystallize bodies by fusion, and our want of success must be attributed to the imperfection of our processes. Most often the crystals are very small, and so grown into each other that the cleavage presents no indication of crystallization: this happens when the liquid is

agitated whilst cooling. When the crystals are sufficiently large the cleavage opens to view their brilliant facets, and people have no hesitation in calling that body crystalline.

Here again it is water which offers us our best example, as if the Creator had designed this wonderful substance to contain in itself, and reveal to observers, the most hidden natural mysteries! When the temperature of the air is sufficiently low, the water it contains is condensed into small regular crystals, which sometimes form a fine white dust, so perfectly transparent at times as to be invisible; it is known to exist, however, by the sensation it creates striking against the face. This condition of ice has been noticed by MM. Barral and Bixio in a balloon ascent. Transported into a moister atmosphere, these little crystals condense water on their surface, and become larger, still preserving their regularity; little by little they grow into flakes of snow of the most various shapes. The celebrated astronomer Kepler was the first to study these forms with care; navigators are especially enabled to study them completely in the polar regions, where the snow falls frequently and at different temperatures. Scoresby has drawn 96 forms of snow, and now several hundreds are known, which are classified. All present the aspect of stars with six rays, symmetrically modified with relation to the centre of the star (fig. 60).

The freezing of water at the surface of the earth follows the same law; but the crystals are so joined one to another as to form masses of ice, in which it is usually impossible to discern them.

The following is a beautiful experiment made by Mr Tyndall, whom we shall assist in a kind of dissection of compact ice, and who will make visible to us the interior work executed during fusion. We have seen how the solid edifice was constructed, we shall now see it as regularly destroyed; its various parts being separated in the same order of succession as that in which they were assembled together, but inversely.

A transparent piece of ice is taken, having two natural parallel faces, which are those which were horizontal whilst the piece of ice was being formed on the surface of the

water; they are called planes of congelation. A pencil of solar rays is directed horizontally on this ice with a mirror, the ice being placed so that its planes of congelation may

FIG. 60.—Various forms of Snow.

FIG. 61.—Dissection of Ice by the Solar Rays.

be parallel with the rays, or, in other words, that the rays may enter by the cleavage. Afterwards place a convergent lens in the path of the rays in such a place that the focus may be formed in the middle of the piece of ice, and notice what passes in the ice with a strong magnifying glass (fig. 61).

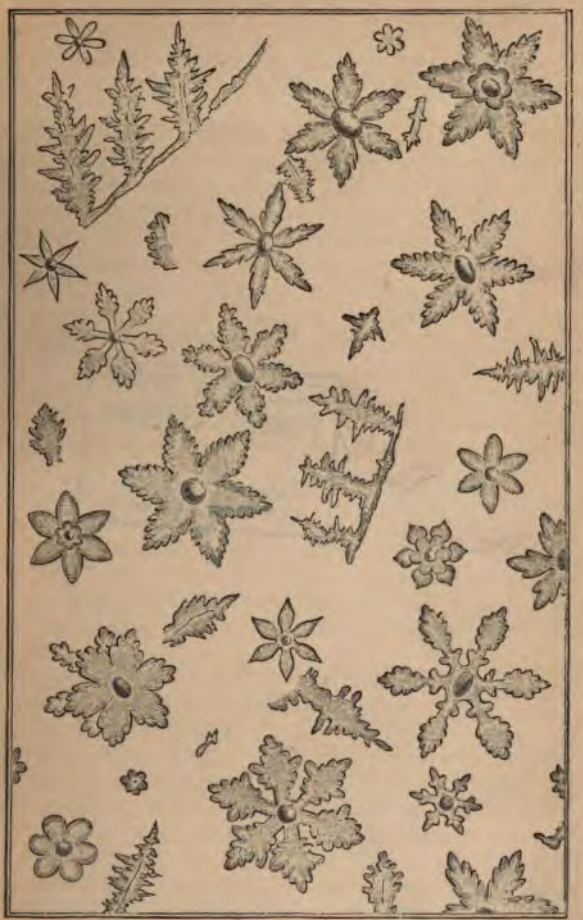

FIG. 62.—Ice-Flowers.

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TILDEN FOUNDATIONS.

Where the rays enter, little stars with six branches, somewhat like flowers, appear rather closely grouped; follow them with the eye to a little distance within the surface at which the rays enter, they will be found more distinctly grouped, which distinctness becomes greater at a still more interior point. These stars may be seen to form and gradually develop themselves. First a little brilliant point appears, which becomes the centre of a round spot; afterwards the rays appear: these increase little by little, and their edges take the form of fern-leaves (fig. 62). The explanation of this phenomenon is as follows:—

The solar rays carry heat to the middle of the ice; but as it gradually penetrates, all the calorific rays capable of being absorbed by the ice are removed, and at a certain depth they cease to have heating powers. This property of radiant heat we have already studied in our fourth chapter. The ice then is more heated near the point where the rays enter than at a certain distance from this point.

Each brilliant point that appears is due to the commencement of fusion at that spot. As the fusion continues round this point the star appears. Each row of molecules is detached in its turn, and as they were arranged symmetrically in three principal directions, we find in the rays of the liquid star the indication of this disposition of the molecules.

It is in these three directions that the molecular forces give way soonest to the action of heat, as if they were those in which the *struggle* was concentrated. We are able to distinguish the water produced by fusion, because it reflects light towards our eye, and we perceive in the centre of the star a point having a metallic appearance, because it is formed by an empty space, which reflects light abundantly.

Why does this empty space occur? We already know that ice is less dense than water; each star consists of a small bulk of ice which has been melted, and the water produced occupies a smaller bulk. It is thus that we find in the details of this phenomenon much useful instruction. Nature is one grand harmony. In the words of Mr Tyndall, "she lays her beams in music, and it is the function of

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FIG. 63.—Exhibition of Ice-Flowers by projection.

science to purify our organs so as to enable us to bear the strain." *

The formation of ice-flowers may be made visible to a great number of persons at once. Solar rays must, in this case, be made to enter the piece of ice perpendicularly to the planes of congelation, and a lens be also placed on the other side of the ice (fig. 63), so that the reversed image of the ice may be projected on a white screen. The experiment is to be made in the dark, and after some wavering, the stars will be found represented on the screen; they are detached as faint shadows on a light ground, because the water absorbs more light than the ice; the empty space is marked by a white point, because it absorbs no light whatever. The solar rays may be substituted by those of the Voltaic arc, or of a Drummond's lime-light.

3. *Change in volume and exterior resistance.—Expansive force of ice.*

The change in volume which accompanies fusion results from the new arrangement of the molecules, which takes place when they are

* Heat as a Mode of Motion, p. 112.

under the action of heat, and the character of this change depends on their form. There is no *à priori* reason for supposing that a body should augment in volume by fusion. Experience decides this question, and reasoning may afterwards lead us to some conclusion respecting the form of the molecules.

It will be sufficient to remark that ice floats on the water provided by its own fusion, to convince us that it diminishes in volume when melting: because a body which floats on the surface of a liquid must have a density inferior to that of the liquid, and, in consequence, a certain weight of this liquid occupies a smaller volume than the same weight of the body. For example, it has been found that a kilogramme of water at the 0° C. (32° Fahrenheit) occupies about a thousand cubic centimetres, and that the same weight of ice at the same temperature measures 75 cubic centimetres more.

The fusion of sulphur offers an example of the contrary effect. The solid fragments of sulphur not yet melted, sink to the bottom of the sulphur that has been already fused. It follows that they are denser than the liquid, and hence that sulphur expands when it melts.

The behaviour of some other fusible bodies resembles that of ice: for example, bismuth and type metal; some, like sulphur, expand—and the number of the last is very great. Inversely, the liquids of the first class expand on solidifying, and those of the second contract. Metals of the first class are best adapted for castings, because at the moment of solidificaton the expanding liquid exactly fills all the cavities of the mould, and in consequence faithfully reproduces its details.

It is the character, in the change of volume to greater or less which determines that of the exterior work when the body is subjected to a surface pressure. We have neglected to take account of this work in the case of substances fusing in the atmosphere. But bodies may be submitted, with the help of convenient apparatus, to very great pressure; the overcoming of these pressures influences, to a notable extent, the heat of fusion.

In the case of ice, there is, at the time of contraction, an

expenditure of exterior work, and a creation of heat. This heat is employed to fuse a part of the body; consequently, the heat coming from without serves to melt the rest, and less is required than if the ice were free from pressure. Compressed ice may be said to melt more easily than ice under ordinary conditions, and it may be supposed that the temperature of fusion is no longer the same as that at which it froze. In fact, M. Mousson has seen it melt at 18° below zero Centigrade (about 0° Fahrenheit) under a pressure of several thousand atmospheres.

In the case of wax, on the contrary, which ordinarily melts at 63° C., and expands by fusion, the exterior work is produced by the expansive force of the molecules of the body, which overcome the exterior pressure; this work consumes heat. In consequence, the heat coming from without serves partly for the execution of this work, whilst the remainder is consumed in that of the interior work. Compressed wax may be said to melt less freely than ordinary wax, and it might be supposed after our experience in the case of ice, that the temperature at which wax melts when under pressure is above 63° C. This has been found to be the case by Bunsen.

That which happens in the case of the solidification of liquids relative to the exterior work, should now be found easy of comprehension. It is only necessary to imagine the reverse of the above effects.

Such is the relation found to exist between the two kinds of mechanical work effected during the passage from the solid state to the liquid state, and *vice versâ*. A number of phenomena will now be explained which otherwise would appear exceptional. The discovery of this relation is an immense step in the study of the intimate constitution of bodies.

We meet with a fresh proof of the energy of the interior forces in the expansive power possessed by the solid or liquid bodies, at the moment in which they pass from the one state to the other. Try to melt sulphur in a vessel hermetically closed, and made of some resisting material, we shall find that the vessel will be broken, supposing it to

have been filled. The molecules of sulphur find themselves opposed to two contrary forces: the heat arriving from without, which tends to separate them from one another, and the resistance of the vessel which opposes itself to this separation,—and the last is conquered.

Some very curious experiments of this nature have been made with water, which expands on solidifying. Fill a cast-iron tube with water, closing it strongly with a screw stopper, and expose it to considerable cold. As the water loses its heat, its molecules change their position, and tend to constitute ice; but for this they require greater space than that

FIG. 64.—Expansive force of Ice.

afforded by the tube: they therefore press against its sides, so forcibly as to split it, through its whole length, with somewhat of an explosion.

An officer of artillery made the following experiment at Quebec. Having filled a bombshell, about fourteen inches in diameter, with water, he closed it by driving an iron peg firmly in, and left it exposed to frost. The stopper was soon driven out to a distance of more than a hundred yards, and a cylinder of ice, eight or nine inches long, issued at

tinuous and transparent block of ice is thus obtained, having the form of the cavity of the mould. By using suitable moulds, lenses, spheres, cups, or statuettes of ice may thus be made.

It is natural to seek the explanation of this last experiment on the effects of compression. We have learnt that

FIG. 67.—Moulding Ice.

ice when compressed melts at a temperature below its freezing-point; in consequence, supposing two fragments of ice at this temperature submitted to pressure in the mould, we may imagine that at the point of contact fusion takes place, because the temperature of the ice is above that at which it melts when under pressure. The water arising from the fusion is therefore below the usual freezing-point; it fills up the interstices of the fragments, and being thus freed from the compressing force—because the fragments do not transmit the pressure equally in every direction—it again becomes solid. Continuity is thus gradually established throughout the mass. The two facts upon which this theory is founded are true: water at the freezing-point, or even a little below, when under strong pressure cannot be in the solid condition; water below the freezing-point, not under pressure, cannot keep the liquid state. But if these laws take a part in the regelation effected within the

mould, they can scarcely be supposed to influence the first experiment where pressure was exerted by the hands, simply to insure contact; this slight pressure would surely be insufficient to lower the temperature of fusion to any considerable extent.

The following explanation of one of the principal causes of regelation by simple contact is given by Tyndall. He took a piece of ice containing natural cells in which a liquid part could be distinguished, and also a gaseous part, which always rose to the upper part of the cell (fig. 68 A). By plunging the piece of ice in warm water and attentively watching its fusion, Tyndall saw the cells diminish considerably in size at the moment in which their envelope of ice melted, when each let a little bubble of air escape, which, excessively reduced in size, rose to the surface of the warm water. It must be concluded from this that the liquid in the cell arises from the fusion of the ice originally surrounding the bubble of air; by its contraction it has enlarged the capacity of the cell in which the bubble of air remains in a rarefied state. But now how can fusion be determined around a bubble of air without the surrounding parts ceasing to be solid?

To answer this question, Tyndall exposed a piece of ice similar to the preceding to considerable cold. The liquid part of the cells congealed, and the bubbles of air diminished in bulk, thus confirming the preceding theory. He next placed a piece of ice in a warm but dark room. After some hours the bleb of water made its appearance in the cells. Heat can therefore pass by conduction from without to the interior of a piece of ice, and thus melt the sides of the cells.

Lastly, by exposing to the rays of heat from a fire a piece of ice containing air-bubbles, Tyndall observed fusion to take place very rapidly around each bubble of air, and the side of the cells to take indented forms, sometimes very pretty, in the superficial parts first reached by the radiant heat (fig. 68 B). He could not obtain the same effect with the obscure rays of heat. Thus fusion may also be determined in the interior of ice by the radiation of luminous heat.

We conclude from these experiments that heat can penetrate a block of ice, either by conduction or radiation, and determine fusion by coming in contact with the bubbles of air imprisoned within the mass, whilst leaving the surrounding ice in the solid state. This may be explained as follows: the molecules situated in the midst of other molecules of ice, are less free in their movements than those

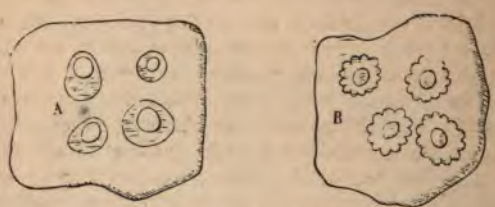

FIG. 68.—Air-cells in Ice.

which are in contact with the air. When heat reaches the exterior surface of a block of ice, a part acts on this surface, and another part continues to travel till it reaches the bubbles of air; there only does it produce an effect, exactly as a blow delivered at one end of a row of billiard balls causes the last ball at the other end to jump forward, whilst the intermediate balls remain at rest; each of them receives the impulse, and transmits it to the next without itself moving; the last only is put in motion, because it does not encounter an obstacle. The fact observed by Tyndall may be expressed in a general manner in the following words. The fusion of a solid body is easier in the superficial parts, and in those which present a solution of continuity, than in those which are altogether continuous, as if the temperature of fusion was less high on the surface of a solid than in its interior.

To apply this remark to the phenomena of regelation. We place two pieces of ice in contact: the two surfaces being kept together exercise one over the other a coercive *action* which opposes itself to the continuance of fusion. *The surface* molecules lose their liberty by ceasing to be

superficial, and becoming interior; their mutual attraction re-establishes the solid condition, and they become cemented together, so long as sufficient heat does not reach them to raise their temperature above the freezing-point. The two pieces are thus united into a single block, and fusion will not take place at any point of the homogeneous ice, until the neighbouring parts are melted in regular order from the superficies.

The child who makes a snow-ball repeats the experiment of regelation. The flakes of snow become converted into little pieces of ice which unite one to another; the hand crushes them, and changes their position; they regelate afresh, and in this manner the light and delicate snow becomes converted into a hard and compact body.

The traveller who visits the glaciers of the Alps, encounters a deep crevasse: he collects snow at the edge of the precipice, he makes a bridge of it, then he mounts this improvised structure, and slowly advances over the abyss. The frozen snow bends under his weight; its parts separate and again regelate; the compressed mass becomes firm, and the passage may be effected in comparative safety. Let us here pause for a moment, to regard the magnificent spectacle presented by the eternal snows; it is not merely a spectacle, but a phenomenon which presents us with a wonderful example of the properties of ice. On the tops of high mountains the aqueous vapour in the atmosphere condenses in the form of snow, which eternally covers their crests. Sometimes the masses of snow descend the declivities as avalanches, with a noise as of thunder, and fill the valleys; sometimes they slip along slowly, and accumulate at the base of the declivities in compressed masses. The air imprisoned in the flakes of snow is little by little expelled, and the mass becomes still more solid: it presses heavily on the rocks at the bottom of the higher valleys, and descends gradually towards the lower. Here, in consequence of the increased warmth, it again attains the temperature of zero, and commences to melt. Then regelation takes place on an immense scale, because the bottom of the valley and the sides of the mountain present an obstacle to

the gliding of the ice. Continually impelled by weight, its mass may break in overcoming the obstacles to its progress, and immense and deep transverse crevasses result from the rupture. Soon, however, the downward pressure of the consolidated snow and ice causes the sides of the crevasse to meet, and regelation takes place. In the meantime other crevasses are produced by the same causes, and, the downward pressure continuing, are again compactly closed by the law of regelation. Thus the glacier moves slowly down the valley at a rate of progress varying from fifteen inches daily in the winter, to thirty inches in the summer, dragging here and there the debris of rocks which have yielded to its efforts. Having thus descended low enough to a warmer region, it melts at its surface and in its depths. and becomes the source of a river. A movement, as eternal as the snow, continually brings down fresh masses of ice, which gradually melt, whilst higher up the loss by fusion is compensated by frequent snow-falls. From this description of the facts, it is obvious that the *glacier* properly so-called, is below the line of perpetual snow; whilst above that line is the mass which feeds it. called the *nevé*.

For a long time it was supposed that glacier ice was of a viscous nature, or plastic, like clay mixed with water: this was the best explanation that could be offered of the phenomena it exhibited in its gradual descent, moulding itself to some extent to the shape of the valley which it filled. But the experiments of which we have just spoken, give the true explanation. The ice breaks into fragments as it descends, and these fragments regelate at the points where they again come in contact.

CHAPTER VIII.

CONCERNING EVAPORATION AND EBULLITION.

1. *Superficial evaporation of solids and liquids.*

CERTAIN solids and liquids are volatile, vapours rise from their surface which spread into the surrounding space, and which have the general properties of all gases, expansibility and compressibility. By virtue of the first their particles always tend to separate one from another, and by virtue of the second they are very easily compressed, and made to occupy a less space. The phenomena which constitute evaporation can sometimes only be recognised by means of experiment. We can only observe it in ordinary circumstances, when the vapour has some characteristic action on our senses. To return to an example already indicated in Chapter I. : a piece of camphor is inclosed in a well-corked flask, or bottle ; its volatility is hardly to be recognised by the first glance at it. But uncork the flask, the characteristic odour of this substance is immediately manifested, and you conclude from this that some of its particles have been detached, and have produced the sensation of smell by coming in contact with your nose. Giving a little more attention, the flask, if it be not too small a one, and if the piece of camphor be allowed to remain a short time, a slight deposit of little brilliant particles may be observed on some parts of its sides. On presenting these parts to the fire, the deposit will disappear, and will be re-formed on the cool side of the flask ; that is to say, on the side furthest removed from the fire. If the heat still continues to act, and reaches

the piece of camphor at the bottom of the flask, the deposit will augment on the cool side; the particles will grow into little crystals of a geometrical form, and at the same time the piece of camphor at the bottom will have diminished in volume. With a sufficiently correct balance, it will be easy to prove that this piece has lost some of its weight, and that the loss is equivalent to the weight of crystals deposited on the sides of the vessel. You will thus have made a true physical experiment. Having become aware of one of the properties of camphor by simple observation, you have studied this property by modifying the circumstances in which the phenomenon has occurred, and you have thus discovered one of its laws. It remains for you to complete your study by a theory which will account for the fact. The particles of camphor may be said to be transported, by the influence of heat, from the surface of the solid piece, to the side of the flask. They were first detached from this surface, separated from one another, thrown out in some manner in every direction; they then collected together at a part where there was not sufficient heat to prevent their union, and reproduced solid camphor. We cannot see the particles during their transport, on account of their extreme minuteness, and their diffusion, but we have proved the final result of the transport, and we conclude that heat volatilizes camphor, causing it to assume the condition of gas or vapour, invisible like the air; while cold reduces the vapour of camphor to the solid state. We observe two inverse transformations, analogous to the fusion and solidification of liquids.

By repeating the same kind of experiments on a number of solids, the same conclusion would be arrived at. Iodine substantiates the preceding theory, by the production of a beautiful violet-coloured vapour. This brownish substance, when slightly heated in a flask, fills it with violet vapour, which slowly condenses in the form of little brown crystals on the cooler portions of the surface. Remove the heat altogether, and in a short time the vapours will disappear, leaving the unvolatilized portion of the iodine *at the bottom,* and the crystalline deposit on the sides.

But the most numerous examples of vaporisation are to be met with in liquids. We have already mentioned several instances in our first chapter, and we shall now pay studious attention to this phenomenon.

Heat a small vessel filled with water; we shall soon observe a slight cloudy vapour above its surface. This cloud is not really vapour: it is composed of a great number of little drops of water, which may be collected, for instance, on a pane of glass, where they form a liquid layer. The phenomenon is analogous to that we observed in the case of camphor and iodine. Under the influence of heat the surface-particles of water are separated from one another; they rise from every part in the form of invisible gas, and disseminate into the air. But coming in contact at a certain height with colder air, they condense again, because heat does not then oppose their union, and they form the light cloud which we see, and which really consists of minute water-drops. We may conclude from these observations that heat causes water to evaporate, and, inversely, that cold condenses the vapour thus formed.

Is it necessary in order to produce vapour, or separate the superficial molecules of a body, to apply heat? Do the molecules yield only to heat, to the natural antagonist of the force which binds them together? The answer to these questions will be found in our further study of the phenomena.

The little cloud above our hot water seems to be permanent. If the atmosphere be still, it is but slightly agitated, it breaks up, disappears at one point and reappears at another; it resembles a light, mobile body floating in the air. On looking at it a little more closely, we find that the cloud is not always the same, but that it rises and disappears, and thus gives place to a new cloud, which is seen to rise in a form different from the first. It is the continued renewal of the drops of water at nearly the same spot that gives the appearance of a persistent cloud; looking at it from a distance, we were deceived by an optical illusion, and we now see what really happens of which the following is the explanation:

When a tiny drop of water has been formed by the cooling

We meet with a very simple domestic application of this property of vapour in Papin's digester. This apparatus is composed of an iron or copper vessel (fig. 70), having very thick sides, which can be closed hermetically with a cover of the same metal by making use of a pressure screw. This

FIG. 70.—Papin's Digester.

cover has a hole, which is closed by resting a lever on it, on which is hung a weight. Water is put in this vessel, and it is then placed over the fire. Vapour forms on the surface of the water and mixes with the air inclosed in the interior; by removing the lever for some moments the mixture of air and vapour is allowed to escape, and soon nothing remains in the vessel but a mixture of vapour and liquid. The lever is replaced, and thus the conditions are obtained of a space empty of air which contains aqueous vapour with

may be known to have taken place when we see the vapour in contact with an excess of its liquid.

The maximum elastic force of the vapour of any liquid is so much the greater as the temperature is higher. The quantity of vapour capable of saturating a given space follows the same law. We have supposed above the ether to be at 60° F.; at 68° F. the difference between the levels of the mercury would have been about thirteen inches; at 104° F. the level of the mercury would have become six inches higher in the open branch of the tube than in the other, as the pressure of the vapour is there superior to that of the atmosphere. At 140° F. we should mark about thirty-eight inches instead of six, and so on.

When the elastic forces are very great we reckon them by the number of atmospheric pressures they are equal to; what is called the pressure of one atmosphere being capable of sustaining a column of mercury thirty inches in height. The following is a table of the elastic forces of the vapour of water as deduced by Regnault from his numerous experiments:—

TABLE OF THE ELASTIC FORCE OF SATURATED AQUEOUS VAPOUR AT VARIOUS TEMPERATURES.

Pressure in Atmospheres.	Temperatures.		Pressure in Atmospheres.	Temperatures.	
	Cent.	Fahr.		Cent.	Fahr.
1	100°	212°	11	185°	364°
2	121	249	12	188	371
3	134	273	13	192	377
4	144	291	14	196	384
5	152	306	15	199	390
6	159	318	16	202	395
7	165	329	17	205	400
8	171	339	18	208	405
9	176	348	19	210	410
10	180	356	20	213	415

N.B. The decimal fractions are omitted.

determinate state of saturation; it is therefore impossible for aqueous vapour to have, at one and the same time, a temperature below 250° F. and an elastic force of more than two atmospheres. An analogous remark might be made for each degree of saturation.

To resume: there are many liquids, and some solids, which cannot exist freely in a vacuum without the molecules on their surface separating from each other and passing into the state of gas. The number of molecules which undergo this transformation depends on the nature of the substance and on its temperature; it is greater as the temperature rises. When the quantity of gas has become sufficient, it exerts a certain pressure on the surface of the substance, and evaporation ceases. This property depends on the state of the molecules and on their mutual actions; in the interior of a body, each molecule is under the influence, on every side, of other molecules; it is therefore less free than it would be in a free state, to yield to other forces opposed to this action, and it is not astonishing that it behaves differently when under the influence of heat. Heat reigns over the condition of each molecule, and consequently also the temperature of the body; it acts as an expansive force, opposed to the molecular attractions, and it is supposed to be in equilibrium in the interior, whilst it predominates on the surface. In the parts under its domination its effect is entirely to destroy cohesion and to produce that which we have already often called an interior work. In the preceding chapter an analogous difference has been shown to exist between the interior and the surface of a solid body relatively to fusion. As to the cessation of evaporation, it is due to the pressure exerted by the vapour formed, which is a contrary force to the expansive force of heat, and hinders this last from further overcoming the force of cohesion.

To confirm our theory it will only be necessary to prove that evaporation is accompanied by the disappearance of sensible heat, of which we shall indeed find numerous examples in the following chapter. But we must first continue our study of the circumstances under which evaporation takes place.

Again making use of the apparatus (fig. 69) already described, we introduce an excess of ether into the reservoir, allowing the air to remain. The column of mercury in the tube will be seen slowly to be displaced. Vapour is therefore slowly formed, and mixes with the air. After some time the level of the mercury remains stationary, showing that the air is saturated with vapour. By the position of these levels it is concluded that the quantity of vapour produced is the same as if the liquid had been introduced into a vacuum.

We infer from this experiment, that a liquid evaporates in a space containing air, or, to speak more generally, a gas which does not act chemically upon it, as if this space were empty. The only difference is in the rapidity of the process. The production of vapour is instantaneous in a vacuum, and takes place slowly in a gas. The slowness of evaporation in the latter case is naturally explained by the mechanical obstacle which the gas presents to the separation of the molecules of vapour. At first they remain accumulated on the surface of the liquid, and keep together the superficial molecules which tend to separate, gradually extending as their elastic force overcomes the resistance of the gas. In the process of evaporation we have, therefore, under consideration an exterior mechanical work, that which effects the displacement of the gas; and the interior work, which effects the separation of the molecules on the surface of the liquid. But the air or gas acts only by the inertia of its mass, and the vapour alone averts the evaporation.

We have now to consider the more ordinary phenomenon of evaporation in the atmosphere: the air can only become saturated in the immediate neighbourhood of a volatile body, because of the immense extent of the gaseous envelope of the earth. As the same atmospheric strata do not long remain in contact with the body, the latter yields fresh vapours to each rapidly succeeding arrival of fresh air, and soon ends by being entirely evaporated. Its molecul s remain in the state of gas, mixed with the air, until circumstances permit it again to condense. For example, in winter, a dry wind causes the disappearance of ice and snow,

without fusion taking place, because it continually removes the vapour of water produced by evaporation, and thereby renders the latter very active. It is in consequence of this that wet linen can be dried in very cold weather, and even though it be frozen. Similarly in summer-time, a wind happening to come during the night, causes the dew already deposited to disappear. We constantly see the effects of the evaporation of water and other volatile substances. The more elevated the temperature, the more marked are these effects. In the equatorial regions, the vapour of water rises above the seas heated by a burning sun; coming in contact with cold air, it condenses into small drops, which form clouds; these drops, rising higher, carried by the ascending current disappear in the strata of dry air; and the phenomenon which engaged our attention at the commencement of this chapter, is presented to our notice on an immense scale. Very often we are able to watch the slow disappearance of a cloud over our heads: the mist of the morning is dissipated in the middle of the day, either because it has risen and formed clouds, or because the solar rays have evaporated it; and in this case, the sky may remain clear. Side by side with this triumph of heat, we meet with the triumph of the molecular forces; the return of clouds, their transformation into rain, snow, hail, proclaims the reunion of the molecules of water. Leaving the earth, they have accomplished an immense aërial voyage, and have returned to undergo even more marvellous transformations, as we shall shortly see. But let us follow our study methodically, and see if we cannot prove that vaporisation consumes heat.

3. *Evaporation is accompanied by a disappearance of sensible heat.*

When a liquid evaporates near a source of heat, it is so easy to conceive that the heat transmitted to its surface does the work necessary to effect the change in state, that we need not trouble to make a conclusive experiment on this point. It will be more to the purpose if we devote

our attention to the cases of evaporation, in which there is no apparent source of heat.

Pour a little ether on your hand; it evaporates, and you feel considerably cold: with certain liquids, such as the sulphide of carbon, which is less volatile than ether, the cold would be less, and it would be less again with water, which is still less volatile. There is then some relation between the quantity of vapour formed, and the amount of sensible heat that disappears. This remark will have suggested to the careful reader that the interior work of vaporisation consumes a quantity of sensible heat taken from the non-evaporated portion and the neighbouring bodies, and that this heat is proportional to the work. An idea of the amount of effect produced may be formed by enveloping the bulb of a thermometer in a piece of linen, and soaking the linen successively with the several liquids above-mentioned. By moving the thermometer about so as to favour an active evaporation, the full temperature in each case may be measured. The result will be exactly the same as that deduced from the sensation of cold felt in the first experiment. With ether, the temperature will fall several degrees below the freezing-point of water; with water it will fall a few degrees only below the ordinary temperature. It is easy to understand that the amount of disappearance of heat, and the quantity of vapour produced in similar experiments, may be measured, and their proportion verified.

If vaporisation consumes heat, the condensation of vapour should, reciprocally, create heat; for, clearly, this condensation represents the expenditure of a molecular work, and we know that such an operation is habitually accompanied by the production of heat. We shall presently find some proof of this assertion. Indeed, do not certain every-day operations, which escape no one, already provide us with one? The temperature of the air, for instance, is considerably milder in winter after rain; and how is it that this rain produces heat, if it is not because the atmospheric water vapour is condensed into liquid drops?

4. *Ebullition under a constant pressure.—Law of Temp*

A third method of transforming liquids into v that of ebullition, or the vaporisation of a liquid acco with the formation of bubbles of vapour throug mass. The investigation of this phenomenon may with the aid of very experiments, and it w plete our study of eva

FIG. 71.—Ordinary Ebullition.

Let us ascertain the sive action of heat contained in an ope such as a glass flask. this, we will place t on a brazier, and im thermometer in it, serve what passes in t (*fig.* 71). The tem gradually rises, and ing and descending spread the heat by con vapour is formed at the which condenses on from the flask as a ligh These phenomena h ready been studied. little gaseous bubbles duced in the middle water, and rise slowly surface; these bubble sist of dissolved air. larger bubbles appear at the bottom from various p the glass; as they rise, they diminish in volume a appear, without reaching the surface; a noise is the which is universally known as *singing*. The explan as follows. Each bubble consists of the vapour o and this vapour is produced around a little bubble when its temperature has risen near the boilir (100° C. or 212° Fahrenheit). As the flask is heated f

bottom, the lower parts of the liquid attain this temperature before the upper parts, and the vapour, formed as it rises, comes in contact with water less heated than itself; it cools in giving up heat to this water, and condenses suddenly; a small vacuum exists for a moment in its place, and the surrounding water rushes into it with a shock; thence a trepidation of the liquid and a noise. At length the bubbles of vapour are able to reach the surface, the thermometer marks 100° C. and the liquid is in full ebullition. Bubbles may be seen to become larger as they rise and burst in the air in the act of raising a thin pellicle of water of a hemispherical form.

The first fundamental law of ebullition is the constancy of its temperature, on condition that we operate as above. Each liquid has a fixed boiling-point in free air, the same as each solid has its temperature of fusion. Thus water boils at 100° C., alcohol at 79° C., ether at 36° C.

It is this constancy of temperature which establishes the difference between evaporation and ebullition; but these two phenomena are only different forms of vaporisation or passage from the liquid state to the gaseous. In each the change of state is effected on the free surface of the liquid, conformably to the principles we have laid down; only, in evaporation it is the visible surface which gives the vapour, and in ebullition there are an indefinite number of little surfaces enveloping microscopical bubbles of air, whether against the sides of the vessel, or in the interior of the liquid mass. It is on these little surfaces that vaporisation is effected. Really, ebullition is only evaporation operating on a large number of points at once.

Many experiments may be made, which prove that ebullition is due to the presence of bubbles of air or other gas. The following are two very curious ones. The first, made by Donny, consists in inclosing water in a bent glass tube, as represented in fig. 72. This tube being open, and drawn out to a smaller diameter at one of its ends, the water is made to boil for some moments, so as completely to expel the air dissolved in the water and that contained in the rest of the tube. Whilst the tube contains vapour and water

only, the point is closed by melting it in a gas fla
allowed to cool, and the apparatus is finished. W
to be used, the part which contains the liquid is
an oil bath, which is heated by means of a lamp. B
a thermometer in the oil, we shall see that the ten
may rise to 130° C. without boiling the water. But

FIG. 72.—Donny's experiment in Ebullition.

this temperature the water is thrown entirely into th
part of the tube, producing a shock which is without
in consequence of the form given to this part.

The second experiment is that first made by M. I
of Lausanne, and it is still more demonstrative. A
water is allowed to fall into a mixture of oils at the t
ature of 100° C. and of which the proportions are so
lated that its density is the same as that of water
same temperature. The water forms a spherical g
the middle of the liquid, and maintains this form wh
temperature is made to rise several degrees above 1c
there is no ebullition, because the drop of water bei
rounded on all sides by the liquid, has no surface for
ation. If the drop be touched by a stick of wood, b

of vapour immediately appear at the point of contact; the reason being that the stick of wood has carried with it some bubbles of air which have come in contact with the water: evaporation has thus become possible, the vapour diffuses into each bubble of air, and enlarges it, giving it such a size that it detaches itself from the wood, and rises to the surface of the oil.

There is a second fundamental law of ebullition which bears evidence to the exterior resistances to vaporisation. We have said that water boils at 100° C. This cannot take place unless the height of the mercury in the barometer is thirty inches. Now this condition is only accidentally filled in countries but little elevated above the level of the sea, and it never is on high mountains. At the top of Mont Blanc the mean height of the barometer is about 16½ inches. Under this pressure water boils at 84° C., and in the same circumstances ether, which boils at 36° C. under the ordinary pressure, boils at so low a temperature as 20°. Generally, the less the atmospherical pressure the lower is the point of ebullition in the open air. The reason of this law is easy to understand: each bubble of vapour in its formation has to raise and overcome the resistance of a surrounding liquid. Now the pressure that the atmosphere exerts on the surface is transmitted by the liquid to the bubble of vapour; and if the depth of the liquid is small, this pressure is the principal cause of resistance. The vapour has to overcome this resistance, and in reality with a somewhat superior expansive force; because it is only when it reaches the atmosphere, there to spread itself abroad, that the two pressures become equal. The bubbles of vapour, therefore, begin to form when the liquid attains the temperature at which its vapour possesses a maximum elastic force equal to the atmospheric pressure. We have already seen that this temperature decreases in the same ratio as the elastic force of the vapour. The effects observed on Mont Blanc are thus explained.

So soon as ebullition commences, the temperature remains invariable, subject to the condition that the pressure does not change. If the pressure augmented on the surface of

the liquid, ebullition would stop for a moment, until the liquid had acquired sufficient heat from the source to raise its temperature to the necessary point. The table on page 187 gives the temperatures at which water boils under various pressures; for example, if it be submitted to a pressure of two atmospheres, its temperature must rise to 121° C. or 249° F. before it begins to boil. In the steam-engine ebullition takes place at a constant temperature, when the fire is managed in such a manner that the quantity of vapour developed in the boiler is constantly equal to that which leaves it to act in the cylinder; it is on this condition that the pressure continues invariable in the boiler, and that the work of the machine is regular. Our table shows the relation which exists between this pressure and the boiling-point of water. If the engine is under a pressure of ten atmospheres, the water boils at 180° C. or 356° F. Suppose the careless stoker should overcharge the furnace with coal, the temperature will rise, because the quantity of vapour formed will be more than that which is able to leave the boiler, and it will therefore cause the pressure to be rapidly augmented. At 202° C. or 395° F. the pressure would be sixteen atmospheres, and at 213° C. or 415° F. would be as much as twenty atmospheres; so that in allowing the temperature to rise 30° C. or 54° F. only, the stoker will have doubled the pressure. Explosion might result from this unless the machine were able to bear so immense a pressure. It is for this reason that the boiler is furnished with safety valves, which allow the vapour to escape so soon as the pressure becomes too great.

5. *Interior and exterior work.—Heat of evaporation.*

What part does heat play in ebullition when the pressure remains constant, and consequently there is no change in temperature? Evidently, the heat ceaselessly furnished by the stove is no longer sensible after passing into the liquid, inasmuch as the thermometer does not give evidence of its presence; it has been consumed, annihilated as heat, but its equivalent will be found in the mechanical work produced

We must here take into consideration both the interior work due to the liquid molecules being separated in spite of the cohesive force which unites them, and the exterior work due to the volume or bulk being increased in spite of the resistance of bodies which press on its exterior surface. When the liquid boils in free air, it is the atmosphere which offers this resistance. When it boils in the steam-engine, it is the piston. In these circumstances, the exterior work is quite comparable in amount with the interior work, and it can never be neglected as in the fusion of solid bodies. This depends on the fact that the bulk of the vapour is always much greater than that of the liquid from which it is produced. Thus water in vaporising at 100° C. expands to a volume 1,700 times its former bulk.

To represent the work produced, imagine a cylinder one square decimetre in section containing a kilogramme of water at 100° C. and a piston exerting on the surface of the water a pressure of 103 kilogrammes. When 536 thermal units shall have been spent, this water will have been reduced into vapour, and the piston will have been raised about 170 metres. The exterior work produced is then more than 17,000 kilogrammetres, and it has consumed 40 thermal units; that is to say, nearly one-thirteenth of the whole quantity of heat expended.

To determine the *heat of vaporisation*,—that is to say, the number of thermal units consumed by a liquid when it is reduced into vapour under constant pressure,—we must measure the heat disengaged by the vapour when it resumes the liquid state under similar circumstances. To illustrate this, remove the source of heat from the cylinder filled with vapour, which has served us in the above demonstration. The result will be that the piston will redescend as fast as the molecules of vapour now disenthralled obey their mutual attractions and reconstitute the liquid. There will be thus two kinds of work spent: first, that of the piston, and afterwards that of the molecular forces; and hence so much heat disengaged as may be equivalent to the whole of this work. When the kilogramme of water at 100° C. has become reconstituted, the total amount of heat disengaged

will be exactly equal to that which had been expended in the vaporisation. The condensation of vapour effected under the same conditions of pressure as ebullition, presents the same relations between heat and work; there is simply inversion in the sense of these quantities. Now it is very easy to measure the heat disengaged: to effect this it suffices to surround the cylinder with cold water. From the weight of this water and the elevation of its temperature, the number of thermal units may be calculated. This is the reason that it is preferred to make the estimation in the return to the liquid state; and it is by making experiments of this kind that Regnault has found that in the operation just described 536 thermal units are expended.

Distillation furnishes a very simple example of the condensation of vapours under a constant pressure. This operation effects the separation of a liquid mixture into its constituents of unequal volatility, the more volatile coming over first. The simplest case is that of a simple liquid in which non-volatile matters are dissolved or held in suspension. The mixture is introduced into a boiler presenting a large surface to the fire. Ebullition takes place; vapour arises from the liquid only; it passes into a serpentine tube surrounded by cold water and open to the air at its extremity, so that the atmospheric pressure is freely exercised within the apparatus (fig. 73). The cooled vapour condenses at first under this pressure, disengaging heat but keeping its temperature. The liquid thus produced descends in the serpentine, gradually cooling, and continues to disengage heat until it has attained the temperature of the water; it is collected in a vessel placed below the apparatus. As to the non-volatile matters, they accumulate in the boiler, being completely separated from the liquid.

The heat disengaged during the condensation of the vapour is employed in heating the water which surrounds the serpentine tube; and as it is necessary, to prevent loss of vapour, that the distilled liquid should issue as cold as possible, the water, as it becomes warm, must be replaced by fresh cold water. This enters from below, and the hot water runs out from above. Such an apparatus is termed a *Still*

It must be remarked that the heat disengaged in the worm is equal to that received from the fire, the mixture having once reached the boiling-point, and loss by conduction, &c., being overlooked. This distillation, therefore, effects a veritable transportation of heat. This operation has been applied for heating purposes. The process of heating by the circulation of steam is nothing more than distillation on a large scale. Suppose a house is to be heated, the boiler

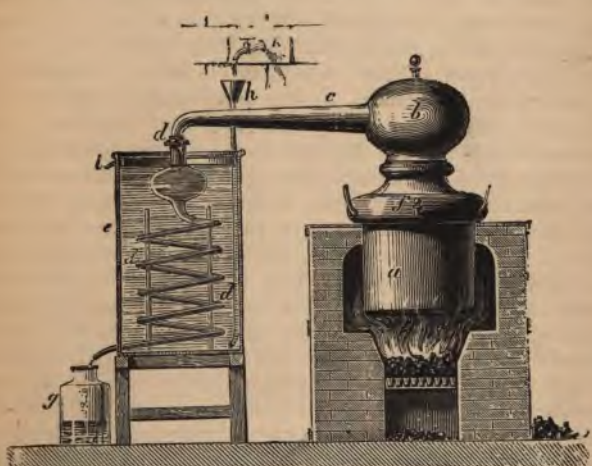

FIG. 73.—Still.

is fixed in one of the cellars, and pipes are arranged in the form of an immense serpentine throughout all the floors of the house, along the walls, and under the floors; the steam rises into them, condenses, disengages heat, and the condensed water returns to the boiler. It again becomes heated and circulates afresh; in the same manner that the blood receives heat from the lungs, distributes it in all parts of the body, and returns to the source to repair its losses.

6. *The utilization of Heat in the steam-engine and hot-air engine.*

A steam-engine furnished with a condenser might be compared to a still, if it were only regarded superficially. There is the boiler, in which the water spends heat to effect its reduction into vapour, and the condenser, a reservoir surrounded by cold water, into which the vapour enters after leaving the cylinder ; the water here again assumes the liquid state, disengaging heat ; and it might be supposed—as, indeed, was for a long time thought—that the heat disengaged in the condenser is equal to the heat expended in the boiler. It has been proved, however, by numerous experiments, especially those of Hirn, to which we have alluded in our first chapter, that this equality does not really exist. The heat disengaged is always less than the heat expended, and the difference is proportional to the mechanical work effected by the piston of the machine, so that the heat taken from the fire by the water in the boiler is partly transported into the condenser, where it heats the surrounding substances, and partly annihilated as heat, and transformed into mechanical motion in the cylinder, where an exterior work is effected. The most perfect machine is that in which the proportion of heat transformed into work is the greatest possible ; and theory indicates that this proportion can scarcely exceed one-sixth of the heat really absorbed by the steam. In other words, taking the most perfect steam-engine known, and supposing that six thermal units are supplied by the fire to the boiler, one unit is converted into work, and five are transported to the condenser, as in a still.

On comparing from this point of view the steam-engine with the hot-air engine, of which we have given an idea in our first chapter, it is obvious that the latter is, theoretically, to be preferred. For example, when the air of the machine is heated but a little above 300° C., which limit is necessary to prevent the parts from being destroyed by rapid oxydation, it is possible in theory to convert half the heat

expended into mechanical work, the other half being simply transported into the surrounding bodies,—a result much superior to that given by the steam-engine. The construction of air-engines ought, therefore, to be seriously studied by inventors, with a view to their mechanical perfection; for, unfortunately, the numerous attempts that have been made to construct large air-engines have been far from realising the hopes that were justly founded upon the advantages they offer in principle. Hitherto, in consequence of their bad construction, and in many cases because the principle appears not to have been grasped, hot-air engines have not exhibited any practical superiority over steam-engines. The future may show a very different result. Hot-air engines are in no danger of exploding; they can be worked without water, and, above all, they effect the conversion of heat into work in the most economical manner. Inventors need not lose courage. With the example of the illustrious Watt always before them, they should rather apply themselves to master thoroughly the laws which have been placed within their reach by the new theory of heat. Was it not, after unheard-of efforts and immense pecuniary sacrifices, that the inventor of the steam-engine arrived at his end; and how many had previously succumbed? Enough to mention here that Denis Papin, of Blois, discovered the principle of this machine in the seventeenth century, a discovery which has immortalized his name, though its application to the industry of the world was the achievement of others.

To return to the phenomena of the steam-engine. It is an experimental fact that a kilogramme of steam, by liquefying in the condenser, disengages a quantity of heat less than that which had been expended in its formation in the boiler. We can explain this by examining the conditions under which the vaporisation of the water and the liquefaction of the vapour are effected. The water is converted into vapour under a constant pressure, and the heat expended serves, on the one hand, to separate the molecules of the liquid, thus effecting an interior work; while, on the other hand, it surmounts the resistance of the piston, and

thus effects an exterior work. The total heat expended is equivalent to the sum of these two works. In the inverse operation, the vapour issues from the cylinder into the condenser, where the pressure is very feeble; the exterior work expended during the diminution of the bulk of this vapour is not considerable, and creates little heat; the interior work spent by the molecular forces at the moment of liquefaction is alone capable of effecting the disengagement of a quantity of heat comparable with the heat spent. It is, therefore, the absence of a sufficient exterior work during condensation which explains the facts observed by Hirn.

We thus see that a vapour when condensing under a constant pressure, or under a gradually decreasing pressure, does not disengage the same quantity of heat that had been absorbed in its formation, and this observation leads us to study ebullition under analogous circumstances.

7. *How a liquid may be made to boil by cold.*

It is not necessary that a liquid should be in contact with what is commonly called fire in order to boil. There are two conditions necessary and sufficient for ebullition: first, that the temperature of the liquid be below the surrounding bodies; secondly, that the pressure exerted on its open surface be less than, or at most equal to, the maximum elastic force possessed by the vapour at the temperature under consideration. In fact, around each little bubble of air contained in the liquid, vapour tends to form as soon as it is reached by the sensible heat from the surrounding bodies, and it is hindered in its formation by the pressure exerted on the bubble of air by the surrounding liquid: a pressure which results from the action on the parts comprised between the bubble and the surface, and from the resistance of the air or gas situated above this surface. The state of the liquid molecules under the double influence of heat and of pressure is comparable to that of a stretched spring. If the obstacle which holds it offers a limited resistance, it will be overcome by a gradually increasing

tension, and the spring will relax itself suddenly. Similarly the molecules (of water, if we please) are gradually heated by neighbouring bodies, and this heating continues so long as their temperature is lower than that of the surrounding bodies, and there arrives a moment when they separate, surmounting the exterior resistance; obviously they possess

FIG. 74—Ebullition *in vacuo*.

at this critical moment an elastic force at least equal to the resistance they overcome.

This reasoning shows that ebullition is not always effected under a constant pressure and an invariable temperature, as in the cases with which we have as yet been occupied.

Connect a little glass flask containing ether with a large reservoir by means of a leaden pipe (fig. 74). This reservoir is closed by a stop-cock, and the air which it contained has been removed by the air-pump. Open the communication, and we shall soon see the ether boil with as much activity as if we had held the flask over the fire. If a thermometer

has been placed in the liquid, we shall see at the same time that the temperature has fallen several degrees. In fine, when the ebullition has lasted a little time, it will entirely cease. This observation confirms the accuracy of our reasoning.

Before opening the communication, the ether is at the ordinary temperature, and its surface is pressed by the atmosphere. After communication is made with the empty reservoir, the air in the flask expands, and diffusing itself through the greater space, its pressure becomes comparatively slight. The molecules of ether then become vaporised at the surface of the liquid, because the pressure of the atmosphere has been removed. Vaporisation being effected by the production of interior work, a quantity of sensible heat equivalent to the work disappears, and in consequence the temperature of that portion of the ether which has remained liquid falls. It will now be colder than the sides of the flask and other bodies near it, and consequently these act upon it, as if they were sources of heat: ebullition can, therefore, continue so long as the pressure remains sufficiently small. But the vapour, accumulating slowly in the reservoir, forms in conjunction with the air a mixture the pressure of which is constantly increasing; this pressure offers to the surface of the ether a resistance which is also increasing, and this soon becomes sufficiently great to stop the ebullition. At that moment the resistance equals the maximum elastic force of the ether vapour at the temperature of the flask.

If we cool the reservoir by surrounding it with ice, or otherwise, ebullition will again commence in the flask, because the ether contained in the reservoir is partly condensed by cooling, and the pressure diminishes in the interior. It has, therefore, ceased to obstruct the formation of vapour in the flask. As fresh vapour is disengaged it enters the reservoir and is condensed, and the ebullition may then continue. A true distillation is thus effected without any apparent application of heat, but there is no essential difference between this phenomenon and that exhibited by the Still. This distillation may, moreover, be

effected with a constant temperature of ebullition if the pressure is maintained invariably in the apparatus. Thus the fact that liquid may be made to boil by cold, which appears singular when thus simply announced, is easily explained.

The experiment may be made with water in the following simple manner, without the need of expensive apparatus:—First, water is made to boil in a long-necked flask (fig. 75), so that the steam arising from it shall completely fill the flask to the exclusion of air. It is then corked tightly, turned up, and the neck is plunged into water, so as entirely to prevent the entrance of air through the interstices of the cork. The flask is thus in a cooling condition, so long as its temperature remains higher than that of the surrounding bodies. The vapour over the liquid partly condenses, and there remains only a sufficient quantity to keep the pressure great enough to prevent further vaporisation.

FIG. 75.—Ebullition of water by cold.

This being the state of things, we can make the water boil again by pouring cold water on the flask; for the vapour being thus rapidly condensed, its pressure suddenly diminishes, as if a vacuum had been produced over the liquid, which is immediately seen to boil. When the apparatus has cooled to the ordinary temperature, the water it contains may be again made to boil by applying a piece of ice to the upper part, or by wetting it with a little ether, which, by its rapid evaporation, produces cold like ice.

The decrease of interior pressure thus occasioned again causes ebullition of the liquid.

To resume: the vaporisation of a liquid is effected under the following circumstances:—First, by evaporation in a vacuum, or in a glass, until the vapour formed from the surface has attained a fixed maximum elastic force, depending on the temperature; secondly, by ebullition at a constant temperature when the pressure is itself constant, and this temperature is below that of the surrounding bodies; thirdly, by ebullition in a vacuum or in an artificial atmosphere of gas the pressure of which is less than the maximum elastic force of the vapour which is relative to the temperature of the liquid.

All liquids are not susceptible of being transformed into vapour by ebullition. Mercury may be made to boil at 360° C. or 680° F., but the less fusible metals, such as gold and platinum, would require temperatures so high as to be unattainable. All that we can say of these bodies is, that they are volatile at very high temperatures: further, many liquids are decomposed by heat, and their vaporisation is consequently very difficult; their distillation often impossible. In these cases, above all, recourse is had to distillation in a vacuum, because a very low temperature, at which decomposition does not take place, suffices for the effect. This method is frequently utilized in chemistry.

8. *The Geysers.*

Let us now try to apply the principles we have explained to those impressive natural phenomena which have often been attributed to mysterious causes, and which have so long exercised the sagacity of savants.

Iceland is a volcanic island, in which a chain of mountain rises covered with eternal snows. A dozen volcanoes are distributed along this chain, the best known of which is Hecla. Glaciers descend from the snowy summits and give rise to immense cataracts of water, which spread out at the foot of the mountains and cover spaces of considerable extent, forming vast marshes, the bottom of which is split

up by volcanic action. The water becomes engulphed in these crevasses, and through subterranean channels penetrates into the heart of the mountains, where it becomes heated, and subsequently issues from the craters in torrents of steam. From time to time we meet with smoking lakes and quagmires, upon the surface of which immense bubbles rise, which in breaking throw their froth several yards into the air. In other places there are intermittent jets of boiling water, called *Geysers*. Everywhere, and under various aspects, the action of the central heat is made manifest, apparently as if Nature had gathered together in this desolate place her most terrible engines of destruction.

But forget the noise of the explosions, approach a geyser whilst at rest, and you will see a marvellous well, fashioned by the hand of Nature herself. Let us take the Great Geyser as our example. At the top of a mound some 12 or 13 yards in height will be found a beautifully enamelled basin more than 50 feet in diameter. In the centre of this basin is a well 74 feet deep, and 10 feet in diameter, the sides of which are lined with the same siliceous enamel as the basin. "Over the surface curls a light vapour," says Prof. Tyndall; "the water is of the purest azure, and tints with its lovely hue fantastic incrustations on the cistern walls." Such is the appearance of the geyser in its quiescent state.

When an eruption is about to take place, the well and basin fill with hot water; the ground shakes, subterranean explosions are heard, and the water is violently agitated. Presently the water swells np in a boiling condition, and overflows the basin of the geyser. This is speedily succeeded by the true eruption. An immense column of water and vapour is thrown into the air, and falls back into the basin: some further detonations are heard, and then all is at rest. But this rest is only momentary; the eruptions succeed each other with similar phenomena during several years, after which they cease. Nothing then remains of the geyser but the well, which continues to be supplied with hot water until it has found another issue.

The celebrated German chemist, Bunsen. has attentively examined the Great Geyser, and he has not only explained

FIG. 6.—Theory of Geysers.

its action, but contrived an experiment which reproduces the principal effects.

The apparatus (fig. 76) used for this experiment is made of a galvanised iron tube six feet long, set upright and surmounted by a basin. This tube is filled with water, and heated at two points: first at the bottom by a furnace, secondly at a height of two feet from the bottom, by means of a circular grating. When the water has become sufficiently heated, it is ejected into the atmosphere, and, falling back into the basin, it refills the tube; then a few slight detonations are heard; and it is at rest. Soon, however, the same phenomena repeat themselves, and thus reproduce the intermittent explosions of the natural geysers, which we will now briefly explain.

The water at the bottom of the tube would boil under the

pressure of the atmosphere, augmented by the pressure of the column of water, 6·6 feet in height, at a temperature of 105° C. or 221° F. The water situated two feet higher up the tube, having only to overcome the pressure of the atmosphere and a column of water four feet six inches in height, would boil at about 103° C. or 217° F. But if, when it is about attaining this temperature, it has no longer such a pressure to support,—for instance, if the column of water is removed,—it would be instantaneously converted into steam, its temperature falling to 100° C. or 212° F., that being the boiling-point of water under the ordinary pressure of one atmosphere. Let us, therefore, conceive the water in the tube to be heated to nearly 103° C. or 217° F. at the part next the circular grate, and that at the bottom to be entering on ebullition at 105° C. or 221° F.: in this case, the steam produced will raise the column of water throughout the length of the tube; the basin will become filled, and that part of the water which is heated to 103° C. will be raised towards the upper part; it will then support a column of water less than four feet six inches, its original height, and will be reduced into steam. This steam will completely drive the water from the tube, and in consequence of the suddenness of the effect the water will be projected above the basin as a jet of water mixed with steam. This jet will cool itself in the air, and then, falling back into the basin, will cool the steam remaining in the tube; all the water in the basin will rush into the latter as into a vacuum, with rather a violent shock; some bubbles of steam might form at the point of contact with the hot sides of the tube, but they will be immediately condensed by contact with the cold water: these consecutive reactions will cause the little detonations before the resumption of rest. Sources of heat continuing to act will then re-establish the column of water in the same state as before, and all the phenomena of the eruption will be repeated.

Bunsen has measured the temperatures of the water of the Great Geyser at various depths, and he has found that they decrease regularly from below upwards. The water at nine metres from the surface is only two degrees below the

temperature of ebullition, which corresponds to the pressure supported by this part. It was therefore only necessary that it should be raised two metres to enable it to boil, and thus project outwards the whole of the column of water above it. As to the cause of this lifting, it is due to the elastic force of the steam which arrives at the bottom of the well, conducted there by the subterranean wells from the volcanic depths where they are generated.

This ingenious theory explains all the peculiarities of the geysers. The water which feeds them is charged with a siliceous matter, which is deposited on the sides of the basin as the water evaporates. The well or tube is thus gradually raised, together with the mounds on which it is situated, and lined with a deposit of siliceous enamel. In this manner the geyser must have been slowly constructed by a spring of siliceous water before the eruptions commenced. At first there would be simply a boiling spring, and the crystalline tube and basin would be slowly formed by the flowing over of the spring. The eruptions would first take place when the tube or well was deep enough to contain a column of water sufficiently high to obstruct the escape of the jet of vapour, although not preventing ebullition below. At length, in consequence of the augmentation in length of the tube, the column of water becomes sufficiently high to put an end to all ebullition; the subterraneous vapour then seeks another outlet, and the geyser is extinct.

9. *The spheroidal state of liquids.—How the human body may be incombustible.*

The phenomena which occur when volatile liquids are placed in contact with very hot bodies are very remarkable, and it is but lately that they have been satisfactorily explained. It is possible to plunge the hand into molten lead, touch molten type-metal, pass the tongue over red-hot iron without burning. The workmen in foundries are aware of these facts; and recently, M. Boutigny, of Évreux, has made a special study of them, himself repeating these experiments. The hand must be carefully moistened with a very volatile

liquid, such as alcohol or ether, when it is wished personally to prove these curious effects. Yet the natural humidity of the skin, especially when under the influence of some apprehension, might suffice. It is also evident that the trial must be made rapidly and with considerable adroitness, simple radiation being sufficient to burn the parts of the hand next those which touch the molten metal. The momentary incombustibility of the skin depends on the slight layer of liquid which moistens it: it is this which intercepts the

FIG. 77.—Spheroidal state of Water.

passage of the heat. The explanation of this property of volatile liquids will, however, result from a less dangerous series of experiments that we shall be able to perform with inanimate matter.

Heat a well-polished iron capsule to redness, and drop into it a few drops of cold water; we shall see them collect together into a tremulous globule with rounded edges, which turns continuously on itself (fig. 77); there is no ebullition, no visible vapour, and yet the globule diminishes slowly. There is, therefore, slow evaporation over its surface; but it

may be so slow, that Pouillet has kept for several hours a large platinum dish filled with water. It is the vapour which, enveloping the waters on all sides, prevents immediate contact between the liquid and the hot surface. Escaping first from one side, then from the other, it breaks into the contour of the globule and makes it oscillate ceaselessly; it acts upon it like an infinity of little hidden springs, alternately compressed and extended. Thence the fantastic

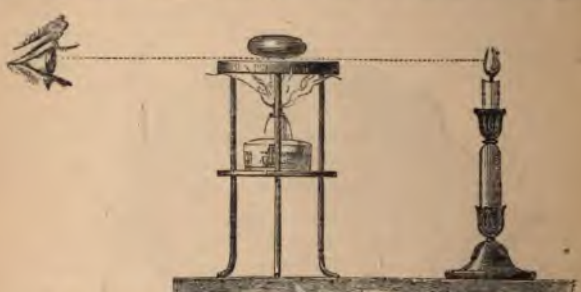

FIG. 78.—Flame seen between the hot surface and the globule.

movements of the globule, which acts as if it were trying to escape from the fire, where it is retained by an invincible force.

It is easy to prove the existence of a slight layer of vapour interposed like a little spring cushion between the incandescent surface and the globule. A horizontal plate of polished metal, silver for instance, is heated by means of a lamp (fig. 78). A drop of cold water being thrown on to the plate when sufficiently hot, takes upon itself the aspect we have just described. Having blackened the drop with a little ink, we may distinctly see the light of a candle through the thin line of vapour which lies between the underside of the globule and the silver plate. A beautiful exhibition may be made of this experiment by projection. By making a horizontal ray of light fall on the globule, and arranging a lens at the other side, a reversed image may be

shown on a screen, in which the plate of silver, the globule, the image of the globule in the plate, and the line of transparent vapour which separates them, are distinctly visible.

The temperature of the water when in this peculiar state (which is called the *spheroidal state*) may be determined by the elevation in temperature produced in a known weight of cold water when the globule is thrown into this water; or by placing the bulb of a thermometer in the midst of the globule—when it will be found that the temperature sought is always below 100° C.; it is therefore impossible for ebullition to take place.

This fact is general:—Put ether instead of water in the heated capsule, and the temperature of the globule of ether will be below 36° C.; it will neither boil nor inflame. Place in it some liquid sulphurous acid, which boils at ten degrees below zero; the globule will be colder by several degrees. A few drops of water thrown on to this globule instantaneously congeals, thus producing ice in a red-hot vessel. This experiment might be made on a larger scale. Place in a platinum crucible strongly heated a large quantity of liquid sulphurous acid: on throwing some cold water into it, a considerable mass of ice may be obtained. Faraday has even seen liquid carbonic acid, which is still more volatile than sulphurous acid, take the spheroidal state at 100° below zero C., or 150° below zero F., and congeal an ounce of mercury in two or three seconds.

This simply proves that volatile liquids, when placed in very hot vessels, cannot attain the temperature of ebullition, and that they only evaporate from their surfaces.

In order for the spheroidal state to be assumed it is necessary that the solid body be heated above a certain limit of temperature, which is special for each liquid, and which is lower in the degree that the liquid is more volatile; according to Boutigny, the limit is 142° C., or 288° F. for water, and 61° C., or 142° F. for ether. If, after having obtained the spheroidal globule, the vessel be allowed to cool at the moment its temperature attains this limit, the liquid immediately touches it and boils with violence. The following is an experiment which demonstrates this fact in a very

striking manner, and which possesses a peculiar interest, because it illustrates one of the causes of explosion in steam-boilers.

A copper bottle (fig. 79) is strongly heated; water is introduced into it, which takes the spheroidal state; the bottle is corked and allowed to cool. When the temperature has fallen to about 142° C the water begins to boil and steam,

FIG. 79.—Explosion produced by the Cooling of Water in the spheroidal state.

developed in great quantity, almost instantaneously ejects the cork with explosion.

Consider now the boiler of a steam-engine. When in a normal condition, its sides which are in contact with water are alone heated by the fire. The water, being thus kept at a constant temperature of ebullition, prevents the metallic sides of the boiler from becoming hotter. From any unexpected cause, such as an incrustation which separates the water from the sides, they will become heated to redness; and if the cause is then removed, if the incrustation presents fissures, the water will again come in contact with the incandescent metal and will take the spheroidal state. When under these circumstances the heating is stopped, the temperature of the metal will fall, and an enormous mass of

vapour will be suddenly engendered at about 142° C. If the resistance of the boiler is not great enough to prevent it, there must necessarily ensue a terrible explosion.

The same phenomenon is presented under another form by the immersion of an incandescent body into the midst of a cold liquid mass. Make a ball of metal, suspended by an iron wire, red-hot, and plunge it quickly into cold water; a kind of crackling will be heard, and the ball will remain red for some time without the surrounding water becoming apparently heated: a sheath of vapour is around the ball which prevents contact. But the ball is presently cooled to the limit of 142° C., and contact is established; immediately, the water nearest boils violently, and a kind of explosion occurs. Glass-blowers utilize this fact; they plunge the mass of incandescent glass held at the end of their rod into water, and, turning it rapidly on itself, they fashion it; afterwards, blowing through their rod, they form in the midst of the pasty mass a bubble into which they introduce a little water, and then close the opening with their finger; the vapour of this water presses the sides of the bubble, swells it, and gradually augments its capacity. All this is done without explosion, because the glass is very hot, and the water which seems to touch it is in the spheroidal state, and evaporates very slowly.

The singular effects we have just proved must now be explained. The experiment has taught us that there is no actual contact between the liquid and the red-hot solid, and that the temperature of the liquid is always below that at which it would boil. It is understood that the vapour produced at the surface of the liquid fills the space which separates it from the solid; but the question arises whether the elastic force of the vapour is sufficient to maintain the separation, and whether the rounded forms of the liquid globules result from their evaporation? It seems more natural to attribute these forms and the absence of contact to the mutual action of the liquid and the solid. A drop of water thrown on to a plane surface covered with lamp-black takes the spheroidal shape without wetting the surface, exactly as if it had been thrown on to the incandescent surface. Does

the generator, bicarbonate of soda is placed, and afterwards a copper tube filled with sulphuric acid, and open at the upper extremity; the reservoir is then closed, and made to oscillate on a horizontal axis. The acid, mixing with the bicarbonate, disengages carbonic acid gas, which soon attains its maximum elastic force, about fifty atmospheres, at the ordinary temperature. A communicating tube is then

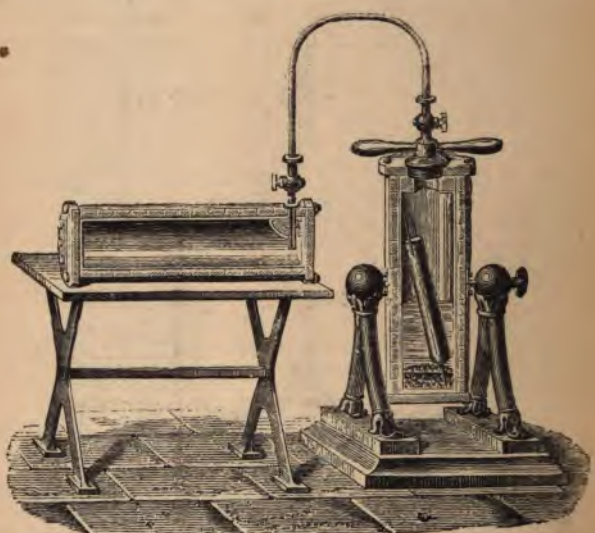

FIG. 83.—Thilorier's Apparatus for liquefying Carbonic Acid.

fitted between the generator and a second reservoir, called the receiver, and communication is opened. The carbonic acid gas passes into the receiver, and there condenses, because the temperature of the generator is always a little higher than that of the receiver, in consequence of the chemical action which is there affected. A true distillation takes place out of the warmer of the two vessels into the

raise the temperature of the liquid; vaporisation consumes nearly all the heat absorbed, and this itself is only a fraction of the heat radiated by the incandescent surface. The greater the incandescence, the smaller is this fraction; because the luminous rays have only a slight heating power. All is thus easily explained, without the necessity of assuming the existence of a new force, as some have done.

The heat employed in the transformation of a liquid into vapour is really annihilated as heat; it is converted into molecular motion, and we shall cite yet another curious example.

It is related that two Englishmen exposed themselves in ovens to a temperature exceeding 100° C., and that they came out safe and sound. There is nothing extraordinary in this experiment if we remember that the human body is a tissue impregnated with water; that this water can come to the surface of the skin by perspiration and there evaporate. When the body is in a very hot medium, the heat is employed interiorly to produce work to prepare perspiration; it can only very slightly raise the temperature. At the surface an abundant sweat protects the skin; it is the water which comes from the interior of the body and which evaporates sufficiently fast to prevent the temperature from rising to a very great extent. The whole of the heat radiated by the oven to the bodies of our hardy experimenters may be said to have been destroyed by perspiration, and we need only be astonished at the audacity of their enterprise.

is effected, a deficit of sensible heat; this heat disappears, and cannot be found in the neighbouring bodies. It is natural to suppose that it has been converted into mechanical work, seeing that it is proportional to the work produced. The following is a very simple example.

A metallic reservoir (fig. 84), closed by a stop-cock, is filled with compressed air. A jet of air from it is directed on to the bulb of a thermometer, and this indicates fallen temperature. If the reservoir were surrounded with water, we should also observe a fall in the temperature of the

FIG. 84.—Cold produced by a Jet of Air.

water, which proves that a part of the sensible heat of the air has disappeared during the exit of the air. This loss has afterwards been partially repaired by the heat which the surrounding bodies furnish to the cold air remaining in the reservoir; but finally both these bodies and the escaped air are minus a certain quantity of heat, of which no portion can be found.

Let us now examine the above phenomemon. At the moment of its escape from the reservoir, the elastic force of the compressed air has lifted the atmospheric air existing before the orifice, and the effect produced is mechanically the same as if the stop-cock were surmounted by a long pipe containing a piston one square decimetre in section, and of the weight of 103 kilogrammes, since the weight of

such a piston represents the pressure of the atmosphere. Suppose the compressed air raises this piston 4 metres, and that then its elastic force has become sufficiently reduced to re-establish the equilibrium; the work produced, in this case, will be equivalent to 412 kilogrammetres. and the thermal unit will have disappeared. The volume of the gas has been augmented to the extent of 40 litres during the same time. Whenever a gas extends itself in the atmosphere in issuing from a reservoir where it is in a compressed state, each augmentation in volume of 40 litres corresponds to a work produced, and a quantity of heat lost, as stated above.

The method of producing cold by the relaxation of gases has been applied to the manufacture of ice. Conceive a machine in which a piston put in motion by a motive force draws atmospheric air into a cylinder, and afterwards compresses it slowly in a reservoir. A certain quantity of mechanical work will be expended in this operation, but the temperature of the compressed gas will not rise if the operation is sufficiently slow to allow the heat created by this expenditure of work to pass away into the surrounding bodies. This heat disseminated in these bodies is not utilizable, and in practice its effects may be neglected. The compressed air afterwards expands rapidly in a cylinder surrounded by water, and its temperature spontaneously falls below zero. It then takes heat from the water; and that again in its turn cools ultimately to zero; after this it can evidently yield no more heat to the gas except by freezing. The working of the machine makes these operations continuous, and they may be summarized as follow:—

First period.—Ordinary air is slowly compressed without change of temperature; this necessitates an expenditure of work.

Second period.—The compressed air expands rapidly and its temperature falls below zero.

Third period.—The cold and relaxed air again returns to zero and to the ordinary pressure, by taking heat from the water which freezes.

On this principle an industrial process has recently been founded in England for the manufacture of ice on a large

scale. A steam-engine works the air-pump, and, according to Kirk, the inventor, a quantity of ice may be produced equal in weight to that of the fuel consumed.

FIG. 85.—Condensation of water vapour by rarefaction of the air.

The relaxation of moist air is a cause of cold which acts by bringing about the condensation of the water vapour it contains, and even its congelation. It is very easy to show experimentally the formation of a mist owing to the action of this cause. It is sufficient to put two glass reservoirs in communication, the one containing air saturated with moisture, the other empty (fig. 85). When the stop-cocks are opened a little cloud may be seen to appear in the first reservoir simultaneously with a whistling sound which the air makes in the act of rushing into the empty reservoir. The mist becomes very apparent when placed between the eye and the light; it appears dim and often surrounded by an iridescent halo.

When any local circumstances determine a diminution of pressure at any given point of the atmosphere, the surrounding air extends and occupies the rarefied spaces: the augmentation of its volume is what we have called relaxation, or letting go from the state of compression in which it had been held. Such is a cause of fog, rain, and even of snow, which we must now add to the other examples that we have already met with in studying the radiation and convection of heat. It is quite evident that the motions of the

atmosphere due to this cause produce local winds, and that it plays a very important part in meteorological phenomena.

The evaporation of liquids furnishes us with a third method for the artificial production of cold, and it is more easily applied than the two preceding ones. It has also been employed by physicists and chemists in the liquefaction of a large number of gases and the solidification of their liquids. Alcarazas are vessels of porous earth in which water can be kept fresh. They have long been used in Asia, and have been imported by the Arabs into Spain, whence they have passed into France. The water contained in these vessels sweats through the sides, and, reaching the exterior surface, evaporates, by consuming some of the sensible heat of the remaining liquid water. The latter may thus fall to the temperature of 10° C. or 50° F., when the exterior temperature is 30° C. or 90° F. The alcaraza must be placed in a gentle current of air, so that the air in contact with the vase may not be allowed to remain and become saturated with moisture. In Bengal, moistened leaves are suspended before the windows; the exterior air being very hot and dry enters the rooms by traversing these leaves; it evaporates the water rapidly and cools sufficiently to acquire a certain degree of freshness. Here, too, we see one of the causes of the coolness of the woods during summer.

During evaporation water may attain the temperature of zero, after which, if evaporation continues, congelation takes place. The heat produced by the part solidified is then consumed by the part vaporised. Each gramme of vapour produced absorbs the heat disengaged by eight grammes of water in freezing. But to produce ice it is necessary to arrange that the water only shall give out heat, and to do this the neighbouring substances which are at the ordinary temperature must be hindered from giving out any considerable quantity. This has been realized by Leslie in a celebrated experiment.

A thin capsule of copper, large but shallow, containing a little water, is sustained by three metallic supports over a vessel filled with concentrated sulphuric acid (fig. 86). This

scale. A steam-engine works the air-p[illegible] to Kirk, the inventor, a quantity of [illegible] equal in weight to that of the fuel [illegible]

FIG. 85.—Condensation of water vapour by rarefaction of the air.

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When any [illegible] determine [illegible] sure at any [illegible] atmosphere [illegible] extends and [illegible] spaces: the [illegible] volume is [illegible] relaxation, [illegible] state of [illegible] had been held. Such is a cause of fu[illegible] snow, which we must now add to the [illegible] we have already met with in studying the [illegible] vection of heat. It is quite evident that [illegible]

...atile liquid than water ... It is, for instance, very ...tion of ether. Water is ... surrounded with cotton ... a glass, and the mouth-

Evaporation of Ether.

...h, which is vigorously blown ... continuously passing over ...ge surface of ether, which thus ... to freeze the ... the tube. ...er by mercury ... ether by ... the mercury ... is which ...mperature of at ... zero C.

apparatus is placed under the receiver of an air-pump, by which the air is then removed. The water evaporates instantaneously in the vacuum; but the evaporation would stop if the vapour formed remained as such in the bell-glass. To prevent this, sulphuric acid is used, which absorbs the

FIG. 86.—Freezing Water by Evaporation.

vapour as fast as it is produced, and in this manner maintains the vacuum. By this ingenious contrivance the evaporation of the water is rendered very rapid, and the surrounding bodies have not time to furnish the necessary heat, so that it is not long before the water remaining in the capsule becomes congealed.

This method has also been applied in England to the industrial manufacture of ice; only, instead of making the vacuum by an air-pump, Messrs. Taylor and Martineau fill a large reservoir with hot steam, the sides of which are afterwards cooled, and the vapour being thus condensed a vacuum is formed. Afterwards they make this reservoir communicate with the vessel containing the water to be frozen, and they absorb the water vapour with sulphuric acid, as in Leslie's experiment.

The evaporation of a more volatile liquid than water produces a much more intense cold. It is, for instance, very easy to freeze water by the evaporation of ether. Water is put in a glass tube, and after being surrounded with cotton moistened with ether, it is placed in a glass, and the mouth-

FIG. 87.—Freezing Water by the Evaporation of Ether.

piece of a bellows is introduced, which is vigorously blown (fig. 87). The current of air thus continuously passing over the cotton acts on a very large surface of ether, which thus evaporates sufficiently fast to freeze the water in the tube.

If we replace the water by mercury, and the ether by liquid sulphurous acid, the mercury may be frozen, which indicates a fall in temperature of at least 40° below zero C.

has found a great number. He has learnt how to melt and volatilize the metals; and later, continually extending his knowledge, he has sought to resolve the same question with every new substance. Hence it has been considered that gases—those subtle matters which are both invisible and inappreciable to the touch, but which manifest themselves by their weight, their elastic force—are really the vapours of certain liquids, and that these liquids might be obtained artificially, although Nature never presents them to our sight. Man has thus become the creator of a number of bodies which he would probably never have met with, but the possibility of whose existence has been anticipated by him. His mind grasps daily new forces of nature, and passes the limits which seemed to have been assigned to him by the Supreme Creator; and each of these specific conquests of his intelligence brings him nearer his Divine Author.

Van Marum was the first to liquefy gas: this gas was ammonia, which is now employed in Carré's apparatus. Since 1823 Faraday has liquefied and solidified a great number of other gases, and as the processes become more perfect the number of those which resist this change in their state becomes diminished. There are now only five that have not been liquefied, and for this reason they are called permanent gases: these are oxygen, nitrogen, hydrogen, cabonic oxide, and binoxide of nitrogen. The first two constitute atmospheric air; so that we as yet only know the latter in the gaseous state: but it is highly probable that in time these constituents of the air will be reduced to the liquid state by combining great pressures with excessive cold.

A fourth method for the production of cold is founded on the fusion of solid bodies. We know in fact that every solid in passing to the liquid state consumes heat. Consequently, if this change of state is effected under the action of other forces than that of the heat of a fire, a part of the sensible heat of the surrounding bodies is destroyed, and their temperature falls. Fusion may be determined by the mutual action of the fusible body and of certain substances with which it may be mixed. By associating such substances *freezing mixtures* are formed.

The most simple consists of powdered ice and common salt mixed in equal quantities. The temperature falls about 20° C. We have more than once had to make use of this method of producing artificial cold.

How is the ice made to melt? The salt is soluble in water: there is therefore between these two substances an attractive action which pre-induces them to constitute the solution. The molecules of ice separate from one another, and this separation is a mechanical work produced, which causes the destruction of a proportional quantity of sensible heat. This heat is at first taken from the mixture, afterwards from the vessel, the air, and neighbouring bodies: their temperature therefore falls. A deposit of ice may be often seen on the outside of the vessel; it is formed by the moisture from the air being cooled, afterwards condensed into liquid drops and finally frozen. The mixture also often appears to fume like hot water in consequence of the moisture from the air being precipitated in the form of mist. This mist does not, therefore, originate in the same manner as that of hot water, because the latter is produced by the steam from the water, as we have explained in our eighth chapter.

So far we have only considered the separation of the molecules of ice; but the molecules of salt act in a similar manner. We all know that a grain of salt disappears completely in a glass of water; that is to say, it loses its solid state by solution and by dissemination throughout the whole bulk of the water. Does not this constitute a kind of fusion which also consumes heat? If so, we should obtain cold by simply dissolving salt in water. Experiment exactly fulfils this prediction. Immerse a very sensible thermometer in water, dissolve some salt in it, and a slight fall in temperature may be observed.

There are many substances more soluble than common salt which produce considerable cold. Nitrate of ammonia, a white substance in the form of long fibrous lamina, produces a temperature below zero when dissolved in ordinary water. If, therefore, we surround a vessel containing pure water with such a mixture, the water may be frozen, supposing the proportions suitable. Such is the principle of

the family ice-machine represented in section in fig. 89. It consists of a metallic vessel which receives the freezing mixture, and of a vessel formed of two cones which holds water to be frozen in the space between them, so that the freezing mixture comes in contact with both the interior

FIG. 89.—Family Ice-Machine.

and the exterior of the vessel. A hollow cone of ice is thus obtained, which may be easily detached by reversing the vessel.

The most energetic freezing mixture known is composed of frozen carbonic acid and ether. With this the temperature may be lowered 100° below zero C. Physicists and chemists have utilized this mixture to liquefy and solidify many substances for which other means were insufficient. We have seen how solid carbonic acid is produced by Thilorier's apparatus. When the object is to collect it, the issuing jet is directed into a brass box formed of two hemispherical parts which may be easily separated, and which are held by hollow handles (fig. 90, *m m*). The gas enters the box by an opening made at a tangent (*d*), and strikes against a

little blade which it causes to whirl in the box; a part of the gas remains there in the state of solid flakes, the remainder escapes by the handles. When the box is full, it is opened and the flakes collected.

Many curious experiments may be made with solid carbonic acid. We have already noticed its spheroidal state and its power of freezing mercury in a red-hot crucible. Some of its other properties are as follow.

Placed on a polished surface, it will fly from the hand when brought near, because the warmth of the hand rapidly vaporises the part nearest to it, and the gas thus escaping

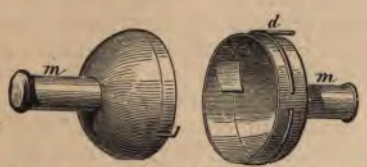

FIG. 90.—Box for collecting solid Carbonic Acid.

almost as a jet from the surface of the fragment causes it to recoil.

It may be lightly touched without any sensation being felt, because contact does not take place; the spheroidal state is at once induced. Neither is there any danger in taking a piece of carbonic acid into the mouth; a cushion envelopes it and prevents it touching the skin. But, as this vapour cannot be breathed, care must be taken to hold the breath when this experiment is made. The flame of a taper may be extinguished by blowing it very gently; the flame is hardly agitated, and goes out quietly because the breath removes the air which is necessary to its existence, and replaces it by carbonic acid gas.

Few phenomena appear more prodigious than this: we may hold in our mouth, without any harm, a body whose temperature is 70° below zero C., and the vapour of which poisons the breath. One must have great confidence in science to try such an experiment, as in venturing to pass

the hand through a stream of molten metal. But the man who loves and seeks the truth, is endowed with a moral force which enfranchises him from vulgar fears; what may appear to others to be odd and foolhardy, is to him the striking demonstration of a natural law; he acts with calmness and reflection under the influence of a profound admiration.

If a piece of this solid carbonic acid is touched with the hand with sufficient pressure to insure actual contact, the hand is burned as if it had touched red-hot iron, and the skin is blackened, proving that the organic tissues suffer a complete disorganization by excessive cold and heat, and that there is little difference between the two cases.

The following experiments illustrate the intense cold of a mixture of solid carbonic acid and ether. A fragment of the acid is deposited on the bottom of a reversed glass, and ether added little by little; a cracking is immediately heard, the glass is broken in consequence of the unequal contraction of its various parts by rapid cooling.

By putting some of the same mixture in contact with mercury, the latter is instantaneously congealed. With the proper proportions, several kilogrammes of solid mercury may be prepared in as many minutes, which may be hammered, cut, or worked, provided it is not touched very strongly, for it would burn the fingers. If moulds are filled with liquid mercury, and then surrounded by the mixture, busts or statuettes of solid mercury may be obtained, which look like silver. There temperature is so low, that they remain for some time in a solid state; fusion takes place very slowly on their surfaces as soon as they are removed from the mixture.

A very curious experiment is to plunge a piece of solid mercury suspended by a thread into ordinary water. The mercury melts, and dissolves itself into an infinity of liquid threads, which, as they fall, freeze the water in their passage; each thread thus surrounds itself with a tube of ice, through which the mercury flows, so long as the fusion continues.

3. *Solution.—Crystallization.*

We have noticed the principal circumstances in which cold is produced, and we now know of the methods at command to induce a given substance to take the solid, liquid, or gaseous state. We have also met with a state of solution in treating of freezing mixtures. We shall finish this chapter with some observations on this state.

The complete study of the solubility of solids in liquids belongs rather to chemistry than to physics; but there is a general physical principle verified in this phenomenon, and therefore we now speak of it. Numerous examples have taught us that the separation of the molecules of a body is a mechanical operation which consumes heat, and that, inversely, their reunion creates heat. The separation may be effected under various circumstances; it is called, generally, *disaggregation;* inversely, the reunion is called *aggregation.* In a solution, the dissolved solid is disaggregated, but the disaggregation which it has suffered must not be confounded with fusion properly so called, which we have studied in Chapter VII.; because not only are the molecules of the solid body separated from one another, but further, they are associated with those of the dissolving liquid, and this second operation is inverse to the first. There are also many instances of solution which are effected without the disengagement of heat. As a rule, there is on one side consumption of heat in the disaggregation of the solid body, on the other side a creation of heat in the combination with the dissolving liquid. The observable effect is due to the difference of these two quantities of heat. If the first is larger than the second, there is a fall in temperature, and a rise if it is smaller. Experiment only would tell us which of these two effects will be produced with a given solid and liquid. Common sugar produces cold when dissolved in water, which may be rendered evident by a very sensible thermometer. When we prepare a glass of *eau sucrée*, we therefore cool our beverage. We must conclude from this fact that it is the effect of the disaggregation of sugar which predominates.

Solutions crystallize under many other circumstances: we have chosen the above example because it allows us to recognise the heat disengaged. Solutions usually deposit crystals by evaporation or cooling, and when there is no agitation, the crystals may grow very large and regular; otherwise they are small, and agglomerated in confused masses. Fig. 91 represents some crystals of alum.

A very pretty experiment in crystallization by evaporation consists in depositing a drop of a saline solution on a

FIG. 91.—Crystallization of Alum.

microscope slide, which is then observed through a microscope. The water slowly evaporates, and the molecules of the salt being gradually deposited by the liquid collect together, and form very regular designs. Every salt has its peculiar form of crystallization. The experiment becomes a very beautiful one when a solar microscope is used, which projects on a white screen an image of the saline drop, magnified several thousand times. The figures formed on the screen by

sal-ammoniac resemble the plan of a large town, with its streets lined with houses, and crossing each other in every direction.

The geysers of Iceland furnish a good example of natural crystallization by solution. We have seen in the preceding chapter that they are produced by a water charged with silica, a substance which constitutes sand and rock crystal, and that this silica, depositing as the water evaporates, gradually elevates the basin of the geyser. We should find in the study of geological phenomena various analogous deposits; for example, those stalactites formed in subterranean grottoes by calcareous matters present odd appearances which excite the admiration of travellers. But the action of rivers is rather to dissolve than crystallize, because the waters are not sufficiently charged with the saline matters to deposit them under ordinary circumstances. It is only in certain lakes and inland seas that the effects of crystallization are met with, as on the shores of the Dead Sea, of which, chemical analysis tells us, one fourth of the total weight consists of salt: it may also be considered as a sea drying itself up. But in the ocean, the proportion of salts dissolved is not a thirtieth of the total weight. These salts have been calculated to represent a solid bed 16 yards in thickness over the whole globe, whilst the water in which they are dissolved represents one of 1,100 yards thick. The ocean is therefore very far from being saturated; it is constantly dissolving a small part of the solid crust of the globe, and it is estimated that the quantity of substances annually dissolved would form a layer $\frac{3}{10000}$ of an inch in thickness over the whole surface of the globe. This dissolving action causes a disappearance of heat too slight, it is true, to give rise to remarkable phenomena, but which must be taken into account in a study of the globe at large.

CHAPTER X.

HEAT UPON THE TERRESTRIAL GLOBE.

1. *Equilibrium of heat on the surface of the globe.—Law of the conservation of energy.*

THE earth is formed of an excessively hot central mass, and of a superficial crust, upon which repose the continents, the seas, and the atmosphere. Every consideration leads us to believe that the central mass is in a liquid condition, while the shell we know is formed of a solid crust, the thickness of which is barely the one hundred and fiftieth part of the total diameter of the earth. An idea may be formed of their relative bulk by imagining a sheet of paper to cover a sphere eight inches in diameter; the sheet of paper represents the solid crust of the earth, whilst the sphere represents the liquid centre. We have shown in Chapter I. that at a certain depth in the solid crust the temperature is invariable through all the changes of season on the surface. Above this region the temperature is subject to both regular and accidental variations; below it the temperature increases regularly with the depth, at the rate of about 1° C. in every hundred feet. Such is the result of numerous observations extending over a period of two hundred years.

The existence of a region of invariable temperature in the solid crust of the earth indicates a state of calorific equilibrium, a compensation between the heat lost and the heat gained by our globe, or at least an excessive slowness in the thermal changes of the molten interior, so that we

can admit the constancy of this temperature when we have under consideration a period of several centuries. We depend on this when we seek the laws of the distribution of heat above the superficial crust, whether at various epochs or in various places. This distribution has the greatest interest for us, since the regulation of living beings depends on it; and we shall now endeavour to trace its principal laws.

The atmosphere, the ocean, and all that part of the earth's crust situated above the region of invariable temperature, are subject to two contrary actions which just balance each other; that is to say, the heating action of the sun and the cooling action of the celestial spaces. The solar rays which strike against the burning sands of the desert are in part reflected, in part absorbed. The absorbed heat raises the temperature of the sand; but so soon as the sun sinks below the horizon, the sand in its turn radiating towards the celestial spaces restores the heat it had received, and compensation is established.

But usually, there is a great number of intermediate operations between the arrival of a solar ray on the earth and the return towards space of an equivalent terrestrial ray; these operations are accomplished both in inorganic matter and in organized beings, and in this manner the solar heat determines life and motion on the surface of the globe. When the sun is absent, the forces of nature are in equilibrium: it is the time of repose. When the sun returns, the equilibrium is broken; a new force excites all the others, and a fresh arrangement becomes necessary. The alternation of day and night is thus an incessant cause of activity.

Through all the evolutions of matter one grand law prevails; namely, the conservation of energy. The energy or power of motion is transmitted from one body to another with neither augmentation nor diminution, and the effects which it produces differing among themselves by their form, are always equivalent. It is only of the effects that we can have any exact knowledge. As to their cause, we have only the sentiment of its existence, and we are totally impotent to assign to it any particular nature. We speak of forces, but

we do not see them; they are the mysterious causes of the phenomena which we contemplate; they emanate from the Divine power, and it does not fall to our lot to have any knowledge of their intimate nature. Our part is to attentively observe the phenomena, and seek the links which connect them.

If we follow the various operations accomplished by solar heat acting upon matter, we shall verify the assertion of the conservation of force in the same time that we sum up the laws treated of in the preceding chapter. A simple drop of water will serve as an example. Leaving the ocean in the form of vapour, it traverses the atmospheric regions, and falls as snow on the glaciers of high mountains; it afterwards redescends as water towards the sea, and in its passage it meets with the vegetable and animal existences, which cause it to undergo marvellous metamorphoses before it is again restored to the ocean.

We will suppose our drop of water to weigh nine grammes, and we will now endeavour to follow it through its successive transformations, according to the data of modern science. When heated by the sun in the ocean it is reduced into vapour, and the heat it consumes represents an expenditure of energy capable of lifting a weight of one kilogramme more than 2,300 metres high. The vapour mixed with the air rises into the atmosphere, where it contributes towards the production of winds and of various effects recognised in the science of meteorology. Gifted with the faculty of absorbing and emitting radiant heat in a greater degree than dry air, the vapour of water moderates, as by a screen, the cooling action of the celestial spaces; thanks to its influence, the atmosphere serves as a garment to the earth. During its stay in the atmosphere our drop of water becomes hot and cold by turns, so that it serves as a kind of vehicle to the heat, and a perfect compensation is established between the heat it absorbs and that which it restores. It soon condenses as a cloud, and then a disengagement of heat takes place. Suppose that the condensation is effected at the same temperature as the initial vaporisation, there will be perfect equality between the heat

disengaged and the heat previously expended in its vaporisation; in other words, the condensation of nine grammes of vapour is equal to the impact of a weight of one kilogramme falling from a height of 2,300 metres. We know that such a blow develops a certain quantity of active energy capable of producing mechanical effects in external bodies. The same effects may be produced by the help of the heat created by the condensation of this vapour; so that, in its transport from the ocean to the cloud, the water has simply transmitted to the atmosphere the energy it first received from the sun. This energy is afterwards transmitted by radiation to the innumerable bodies which fill celestial space.

High mountains condense a large part of the atmospheric moisture. Endowed with considerable radiating power in consequence of the purity and rarefaction of the air situated above them, they cool the surrounding air during the night, and the clouds become heaped around their sides. These clouds also cool by their own radiation, and resolve themselves into snow. The snowy summits which rise above the eternal ice realize on an immense scale the condensation of the vapours formed on the surface of the seas. The ocean and the mountains constitute a true distillatory apparatus, in which the sun is the source of heat or fire. All the ice of our glaciers owes its origin to the water-vapour of the ocean; and the heat furnished by the sun for the production of this vapour is so great that it would suffice to melt five times the weight of iron. We have seen that an equal quantity of heat is created by the simple formation of these clouds. We must now realize the calorific effects which accompany their transformation into snow.

In becoming solid, nine grammes of water disengage heat equal to the blow of one kilogramme falling a height of 300 metres, and that quantity of energy is dissipated by radiation. But the glacier melts in time, and the fusion of nine grammes of ice represents just the reverse operation of the preceding. To preserve an invariable extent, the glacier must lose as much water by fusion as it gains by the condensation of atmospheric moisture, and then a perfect

compensation exists between the heat created and the heat expended. The energy is here derived from the sun, which determines the partial fusion of the glacier, either directly or by the intermediate action of the earth, and it appears simply transferred to the earth from the celestial spaces.

Our drop of water has now again become liquid, but it is at a great height above the ocean—say 4000 metres. We must add to the effects above described the mechanical work which represents the transport of nine grammes to such a height. The expenditure of energy in this transport would be capable of lifting a kilogramme to the height of thirty-six metres, and this also is derived from solar action, corresponding to the displacement of the atmospheric strata, which we have spoken of under the name of Convection. This effect is recompensed by the return of the water of the glacier to the ocean. Gravity causes the drops to collect at the base of the glacier, where they combine and form streams and rivers, and ultimately find their way into the sea. In the descent from a source situated at a height of 4000 metres, nine grammes of water would develop an amount of energy equal to the preceding.

By the simple friction of the bodies which hinder its progress, this water is able to return the heat of which it had previouly robbed the atmosphere. But the forms under which the energy may reappear are varied to infinity: its transformations do not stop there. The river waters the fertile plains, and meanders through a thousand sinuosities in accordance with the inclination of the ground. It would almost seem that the earth instinctively sought to retain these waters in order to nourish the innumerable beings which live upon its surface. The vegetable needs various elements to compose its organs; it needs water for the circulation and elaboration of these elements; it needs also hydrogen. But to fix in its tissues one gramme of this substance, the vegetable must first decompose nine grammes of water. The sun furnishes the motive force necessary to this work, which is equivalent to the elevation of a weight of one kilogramme more than fourteen kilometres high. It is under this powerful influence that the plant appropriates

one gramme of hydrogen. The plant will afterwards serve as food to some animal, in which will reappear all the energy previously expended. Each gramme of hydrogen which is submitted in the blood of the animal to the action of respiration, disengages a quantity of heat capable of elevating one kilogramme to the height of fourteen kilometres, by recombining with the oxygen of the air to reconstitute nine grammes of water. Such is the admirable balance reigning throughout nature, the sublime simplicity of which reveals to us the infinite wisdom of an all-powerful Creator.

To resume: we see that, in the circulation of nine grammes of water through the ocean, the atmosphere, the glacier, the river, the vegetable, and the animal, a work is produced of 16,636 kilogrammetres, and an equal work expended. This represents thirty-nine thermal units, allowing a thermal unit to be equal to 425 kilogrammetres. This heat has been furnished by the sun, and finally it is transmitted to the celestial spaces by the radiation of the earth. Thus as Professor Tyndall has so eloquently shown, we are directly indebted to the solar rays for all the multiplied powers exhibited on the globe. There are so many special forms of the power of the sun, so many mechanical arrangements in which that great motive force exhibits its method of working in the interval, so to speak, between the radiation of heat from its source and its return into pure space.

The time separating the moments which the solar energy is expending from that in which an equal energy is put in activity, may be considerable, so that the energy may seem shut up in certain terrestrial bodies. For example, our coal-mines are the remains of immense forests which have existed on the earth long before the advent of man. Buried beneath the waters by geological changes, they have undergone a slow decomposition, and their carbon has been set at liberty. Each kilogramme of carbon comes from the carbonic acid which the vegetable productions of these forests have decomposed during their life under the influence of the sun, and this decomposition has entailed an expenditure of energy sufficient to raise one kilogramme 3400 kilometres high. We burn coal, and this energy again comes

to light; it has been preserved intact, and we utilize the heat sent, radiated by the sun to the earth thousands of years ago. The utilization is complete when we simply use the coal in a stove for heating purposes. But if we wish to convert the energy into mechanical work, we know that it is impossible in our engines to avoid the disengagement and loss of a large proportion of sensible heat, or to convert all the heat of the combustion into work. We can scarcely raise with one kilogramme of coal burnt under the boiler of a steam-engine a weight of one kilogramme to a height of 135 kilometres; the greater part of the energy is developed in the form of heat. In any case, however, the great principle of the conservation of force is verified by experience.

It is this principle which establishes a correlation between all physical phenomena, because the energy communicated by matter may be manifested otherwise than by heat and mechanical work; it may, for instance, take the form of electricity; but we have been careful to study phenomena in which these forces do not intervene. It is by separating the natural forces from one another, making them act separately on matter, that a knowledge of their laws may be obtained. When science becomes more advanced, it may be attempted to embrace under one formula all the incomplete results now arrived at, and thus prepare a synthesis which should summarize all science.

2. *Distribution of temperature on the earth's surface.—Climates.—Effects of atmospheric moisture.*

Having now acquired a general idea of what is meant by the equilibrium of heat on the surface of the globe, we proceed to consider the distribution of temperatures. If at every point of the earth's surface the amount of heat lost and that gained were constantly equal, the temperature would remain constant. A thousand causes interfere with this equality, and the temperature varies periodically according to certain laws, in such a manner that there is always a conservation of energy. Living beings constantly require the concurrence of heat in a determinate proportion, and also during

thermometer: it indicates the maximum. The other contains alcohol, and indicates the minimum. To effect this the thread of mercury, when the temperature rises, pushes a little iron cylinder forward, which remains in its place when the temperature falls. The alcohol of the second thermometer, on the contrary, contains a little enamel cylinder which it drags by adherence when the alcohol contracts, leaving it, however, in its place when the alcohol expands. The different action in these two thermometers is easily explained: the mercury is incapable of wetting either the iron or the glass, and is therefore unable to pass round the little iron cylinder; whilst the alcohol, wetting both the enamel and the glass, completely surrounds the latter cylinder. Suppose the cylinder placed at the end of the alcoholic column, and the alcohol to contract, it drags the cylinder without ceasing to surround it; if, on the contrary, the alcohol expands, it leaves the cylinder stationary, and itself passes along in the space between the cylinder and the glass tube. When using the apparatus, the end of the tablet on the right is lowered, and the little cylinders are caused by gravity to fall to the extremities of their respective liquid columns. The tablet is replaced horizontally, and twenty-four hours afterwards the position of the two cylinders is noted. The little cylinders are then again adjusted, and so on.

The mean daily temperature of a given place varies according to the season. After the winter solstice, the time during which the sun remains above the horizon increases daily until the summer solstice; and at the same time it rises higher and higher in the heavens in its diurnal revolution. It therefore acts stronger and stronger, until, ultimately, the earth is heated more during the day than it cools at night. At the summer solstice, the solar action has reached its maximum; but the cooling action of the celestial spaces does not yet compensate it: compensation does not occur for some time after, when the solar action is undergoing a decrease in consequence of the diminution in the length of the day and the height of the sun. The daily mean temperature at this moment attains its maximum. Afterwards, until the winter solstice, the earth cools more

during the night than it is warmed during the day, and the temperature falls.

As a crowd of local or accidental circumstances must be added to the above cause, the variations in the mean temperatures of each day become complicated; their effect, however, disappears by calculating the monthly means of several years. To do this the sum of the daily means is divided by the number of days in the month, and hence a monthly rate of mean temperature is obtained. This calculation is made with the means obtained each month during a large number of years. The following are the results calculated by Bouvard for Paris, after a series of observations extending over sixteen years. Instead of the Centigrade scale used by Bouvard, we give the figures according to the scale of Fahrenheit:—

JAN.	FEB.	MARCH.	APRIL.	MAY.	JUNE.
35°.6	39°.2	44°.6	51°.3	57°.2	62°.6
JULY.	AUG.	SEPT.	OCT.	NOV.	DEC.
65°.7	64°.8	60°.6	52° 7	44°.6	39°

These figures show that the maximum is reached in July—that is to say, after the summer solstice. By taking the sum of the monthly means given in the above table, and dividing it by 12, the mean temperature of Paris is obtained; this is 51°.4, which is very nearly the mean of the month of April

This number does not, however, suffice to characterise the action of the sun on a given spot. The extremes of temperature exercise the greatest influence on animals and vegetables. That a plant may not freeze, or that a fruit may ripen, the temperature must be neither too low in the one instance nor too high in the other. Further, it is necessary in this estimate to consider a large number of observations so as to eliminate the influences of accidental causes; and it is by comparing the mean temperature of the warmest month with that of the coldest, that the climate of the place is determined. The preceding table gives us 65°.7 and 35°.6 for Paris; the difference is 30°.1. This figure measures the range of the climate of Paris. Such a climate

is variable, because the absolute temperature may accidentally rise to 100° F. or fall to 10° below zero. Hence exceptional winters and summers that cannot be foreseen in the present state of meteorology.

We shall now consider the causes which influence the mean temperature and climate of the various countries. The farther we go from the equator towards the poles, the more obliquely do the solar rays fall on the surface of the globe. In consequence, their action becomes gradually less intense, and the mean temperature diminishes. When we reach the polar regions, we find the atmospheric vapours are continually condensed to snow, and the surface of the seas is frozen. Immense fields of ice, annually changing their position, put an end to navigation, and render the exploration of these regions almost impossible. Dr Kane overcame these difficulties in his memorable expedition to the Arctic Seas; but, in spite of the efforts of Cook, Weddel, Dumont d'Urville, and James Ross, we have no certain knowledge of the southern arctic regions, where, however, we cannot reasonably doubt there is also a free polar sea surrounded with icy barriers.

The configuration of the continents and the marine currents cause great differences in the distribution of heat in the two hemispheres. In the northern hemisphere we find vast continents extending very nearly to the pole; in the southern hemisphere, on the contrary, Africa and America taper off to points, and present much smaller superficies than that of the seas. The southern extremity of America, the part which comes nearest to the South Pole, is not farther removed from the equator than Denmark. As the sea reflects from the surface a larger proportion of the solar rays than the land, the heat absorbed by the southern hemisphere should be less than that absorbed by ours. This, in fact, we find to be the case at the extreme southern point of America—the mean temperature is lower than that of Denmark.

Seas have the effect of softening a climate. The vapour of water ceaselessly absorbed by the atmospheric air acts as a kind of clothing, which preserves the soil from too great

warmth or cold. Moreover, the marine currents distribute on the coasts the heat which the whole ocean receives from the sun, or carries from them a part of that which the land has absorbed to deliver it elsewhere. Thus the mildest climates are to be met with among islands where the difference between the mean temperature of the hottest month and that of the coldest is not more than a few degrees, and where moderately hot summers are followed by mild winters. Such a climate is called constant; it is met with in South America, where immense tree-ferns grow, and where the magnificent vegetation of the tropics extends much further from the equator than in the northern hemisphere. Hence, in the same mean temperature as that of France, orchids of many curious varieties and vanilla grow freely in those countries, although the same species need the protection of our greenhouses.

In England we find again a very striking example of the influence of moisture on the climate and on the mean temperature, which at London is about 50° F. At Irkoutsk, the capital of Siberia, which is at about the same distance from the equator as London, the mean temperature is a little below 32° F. At London the mean temperature of the coldest month is 37°.4 F., and that of the hottest month 64° F. At Irkoutsk these temperatures are 3° below zero F., and 63°.5 F. above. The differences of these extreme temperatures are thus 26°.6 F. for London, and 60°.5 F. for Irkoutsk. This last town is the type of an *excessive climate.*

It is easy to explain this enormous difference between two localities which, by their position on the surface of the globe with respect to the sun, ought to receive the same quantity of heat. We have already mentioned the influence of the Gulf-stream on the climate of England. This vast marine current carries to her shores the heat absorbed in the Gulf of Mexico and in the equatorial regions of the Atlantic. The atmospheric currents carry in the same direction large quantities of water vapour arising from the evaporation of the ocean: this vapour, condensing in England, disengages as much as had been absorbed in its formation

in the tropics. It is a kind of aërial carrier, which draws the heat from its source and carries it to a distance. At London the south-west wind blows for nine months in the year, and whenever it brings rain it brings additional heat: hence the mild temperature of the climate. Intense colds and excessive heats are alike prevented by the moistness of the atmosphere, which moderates in the summer the ardour of the sun by absorbing its rays, and in winter preserves the terrestrial heat by opposing its radiation towards the celestial spaces. According to Tyndall's experiments, the water vapour contained in the atmosphere would exercise on radiant heat an absorption seventy-two times greater than that of dry air. England, in fact, may be said to enjoy the sheltering advantage of a heaven-built screen; and, if such plants as the vine do not flourish in the island for want of a sufficient heat in the summer, others are able to live there which could not support the cold of continental winters. In the north-east of Ireland, according to Humboldt, the myrtle grows with as much strength as in Portugal; it hardly freezes there in winter, but the summer heat is not sufficient to ripen the grape. On the coasts of Devonshire, camellias pass the winter unsheltered in the open ground, and espalier orange-trees may be seen bearing fruit.*

The circumstances are very different at Irkoutsk. At a great distance from the sea the air there is very dry, and no longer preserves the soil. The winds bring only masses of dry air frozen by the polar regions or heated by the deserts of Central Asia. In winter, Lake Baikal, near Irkoutsk, is frozen during a long time, and may be passed in a sledge during all the period from January to April inclusive. Some very curious details of this country are given by a traveller who visited it in the month of January. The lake—100 leagues long, 15 broad—resembled a petrified sea throughout its whole extent. "Along the coasts might be seen on the sides of the rocks and in the ravines immense icicles, which looked like frozen cascades; these were caused by the foam of the lake, which, breaking on the shores during

* Becquerel's "Elements of Terrestrial Physics and Meteorology."

a tempest, had been frozen before it could fall back." Having started a sledge on this frozen plain, it seemed to our traveller as if he were starting in a post-chaise from Dieppe for America. Under the ice, two or three yards in thickness, strange noises were heard, and occasionally an agitation was felt as if the ice and water were not in contact. The captive waters lifted themselves from the depths, and rushed with fury against the icy vault which covered them. In summer, on the contrary, the temperature at Irkoutsk is maintained often at 80° F. for several weeks, and the lake is navigated by steamers. The south winds would cause much greater summer heat if they were not stopped by the Altai Mountains, which shelter the country from the wind of the desert.

The elevation of a spot is one cause of cold. The air becoming less dense as we rise absorbs less heat, and its temperature decreases. In fact, this is what results from the observations made, whether on mountains or in balloon ascents. Thus, at the Great St. Bernard the mean temperature is 33°.8 F. The law of this variation depends on a number of circumstances; and we must not now enter into any details on this question, nor on that of the height of the perpetual snows, which forms part of it.

The study we have made of the general causes which determine the mean temperature and the climate of different parts of the globe, suffices to show on what principles their explanation rests. We shall finish this book by considering the modifications effected by time on the distribution of terrestrial heat within the historical period, and those which may possibly be brought about in future ages.

3. *The changes which have occurred in the distribution of Heat previous to our epoch.—Geological revolutions.*

In Palestine, in the time of Moses, the date and raisin ripened; from which facts we may calculate approximately the mean temperature of that country at the time. In fact, the date does not now ripen at Catania, the mean temperature of which is 64°.4 F. A temperature of 70° F. is neces-

interior pressure will augment, and the fluid it contains will come out by the fissures.

Such is a rough image of what passes at the present time. Three hundred volcanoes exist on the earth's surface, immense fissures, from which flows incandescent lava, while mixtures of gas-cinders and vitrified rocks are cast out by the fire. The whole mass thrown out in one year measures one cubic kilometre. This result confirms those at which we arrive by other considerations.

But the effect of terrestrial contraction does not stop here. The fluid centre, in contracting, leaves an empty space between its surface and that of the solid crust. It may, therefore, be in a state of continual fluctuation, submit like the ocean to the attraction of the moon, have its tides, its waves, and its tempests. Every imaginable chemical operation might be effected on the surface of this sea of fire; hence the subterranean detonations, the oscillations of the solid crust, and the trembling of the earth, most frequent in the equatorial regions, where the speed of the diurnal rotation is greatest, and the lunar action is most strongly felt. In fine, the unequal thickness of the crust at different points occasions an unequal collapse, and immense fractures take place along the lines of least resistance. At such times a terrible overthrow of the established order of things takes place on the surface of the earth. Wherever there is a fracture a part of the crust sinks in, whilst the neighbouring part rises; a chain of mountains may be created in a moment, and the volcanoes vomit their inflammable matters wherever the earth has been torn open. From this point of view the collapse causes the fracture, the interior empty spaces cause the oscillatory motion, because the broken part of the crust is not sustained, and the volcanic eruption is but the result of this dislocation, because the molten matter enters the fissures only after their formation without having contributed to it.

A similar revolution changes the distribution of the ocean: new continents rise from the bed of the sea, and others sink beneath the flood of waters. Then a fresh period of tran-

quillity commences, until, the collapse continuing, similar phenomena are reproduced.

The researches of Beaumont and of other geologists have shown us the traces of thirteen great revolutions and the order of their succession; but we cannot know the intervals of time which have separated them; we only know that they must be immense. Thus both geological and physical observations perfectly accord in proving the slowness of the earth's cooling. To these proofs we may add another, drawn from astronomical observations.

Supposing that the sun has suffered no change, the contraction of the earth should cause an acceleration of the motion of diurnal rotation, and, in consequence, diminish the length of the day. Now, according to Laplace, the length of the day has not decreased by $\frac{1}{500}$ of a second in the last 2,000 years; this effect is therefore inappreciable.

The distribution of solar heat on the surface of the earth is, on the contrary, subject to great vicissitudes. It is probable that the sun cools as slowly as the earth, and that the quantity of heat which it radiates to our earth is almost invariable; but at each geological revolution this heat encounters fresh continents and seas, and the climates are completely changed. Among the changes of this kind most nearly approaching the creation of man, we have a sinking of the whole of Switzerland, the traces of which have remained on the sides of the Alps and the Jura mountains.

The traveller descending the valley of the Rhone may, if his knowledge be sufficient, trace the remains of ancient glaciers so far as the Lake of Geneva. Here the rocks which border the valley are scratched, and present deep furrows; there they are polished and rounded off; in other places they are streaked and channeled out. They have everywhere the aspect of the rocks we may see bordering existing glaciers, where we may, in a measure, see the ice working under our eyes. What is much more, on the other side of the Lake of Geneva, on the chalky slopes of the Jura, rise blocks of the same granite which forms the summits of the Alps, as if these blocks had been detached from the top, and carried to this distance. We may see at

4. *Future of the terrestrial globe.*

The future destiny of the earth is a high question in natural philosophy which it is not our business to answer. We may nevertheless venture to give a hint of what may possibly happen. It is first necessary to distinguish between simple conjectures and observed facts. Among the latter, we have in the first place the great discoveries which form the science of geology. The time that has elapsed since the creation of man is incomparably less than the interval between two consecutive geological revolutions. Besides, the later geological revolutions have effected fewer changes than the first in the conditions of the existence of organized beings. Having considered the past, we now come to the present. The same phenomena which have formerly accompanied the revolutions of the globe are still happening under our eyes. Add to these facts those which belong to the domain of physics. The sun and the earth are warmer than the celestial spaces, and they follow the laws of heat exactly as all other material bodies; they must be continually cooling so long as they are at a higher temperature than the celestial spaces, although the most delicate instruments afford no indication of this phenomenon. Adding that astronomy confirms these observations, we shall have assembled before us the principal data of the problem. They are quite insufficient, however, to solve it, and if we go farther we immediately begin to hypothecate. If the earth is a liquid globe, covered by a thin solid skin, which sufficiently explains the anterior geological phenomena, the same phenomena should be reproduced in successive centuries; the speed of the diurnal rotation should increase, provided the sun and other celestial bodies continue to act in the same manner on our globe. The flattening at the poles should also increase, and the distribution of heat be thus changed; there should be a greater difference between the mean temperature of the polar regions and that of the equatorial regions. Further, the orbit described by the earth around the sun should become lengthened, so that the winters would become colder and the summers hotter. Once in this vein,

the mind knows no bounds; obstacles seem to disappear as in a dream; the possible seems to be almost without limit. But this is no more than a mirage or play of the imagination. A problem cannot be solved without complete data, but if we are unable to say to what extent the earth may be modified in future ages, it is not impossible to draw certain consequences from facts really observed. It is probable that a geological revolution will not come about within a period of time much exceeding that which has elapsed since the creation of man; and further, that the changes likely to occur will be less considerable than formerly. We conclude, therefore, that the present race of organized beings is less likely to be affected by geological revolutions than even those which characterized former epochs, and are now only known by their fossil remains.

Fear is most often, if not always, the offspring of ignorance and superstition. Thank God, we live in an age when the light shed by science on the minds of the greater mass of the people is sufficient to save them from degrading terrors. Thunder and the sun's eclipses no longer affright civilized nations; we contemplate them with a serenity born with a knowledge of the truth, and an admiration for the works of God; and when nature's grander phenomena present themselves, we know that it is our duty to discover if any and what the peril is, that we may be prepared with all the resources furnished us by an all-wise Providence. Thus scientific investigation fortifies within our soul the sentiment of adoration for the Divine Power, and raises us by degrees from the slavery of the physical to the freedom of the moral and spiritual world. Thus science and religion may truly be called sister spirits.

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For specimen illustration see page 28.

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Fig. 55.—Wizard Dance.

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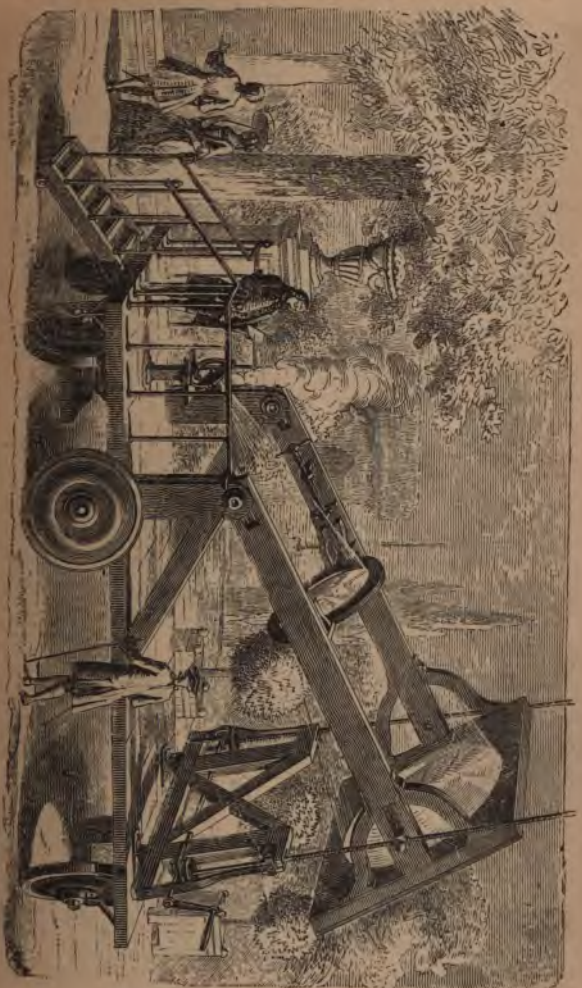

FIG. 25 a.—Bernieres' Immense Burning-glass.

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